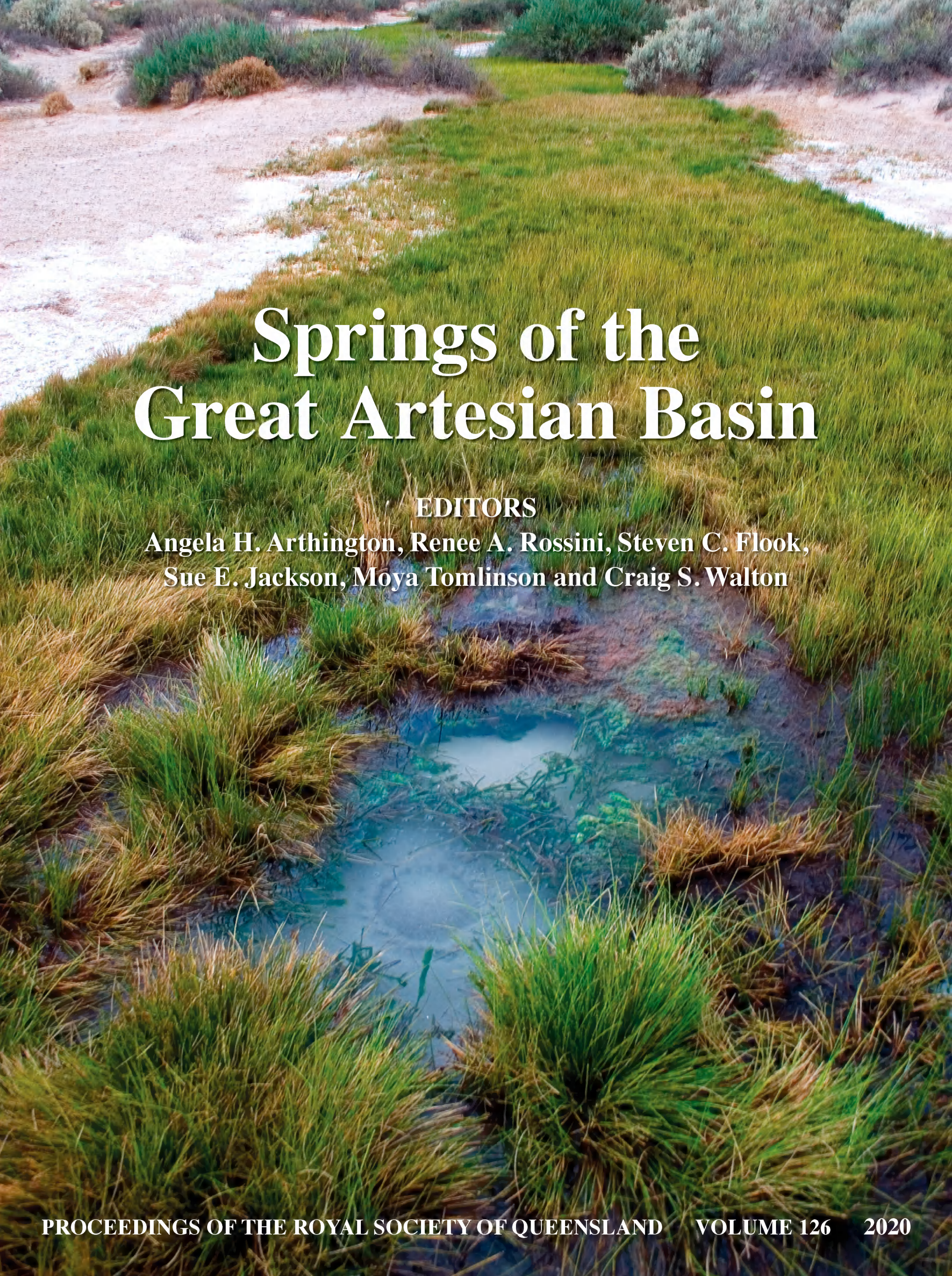

Springs of the Great Artesian Basin

EDITORS

Angela H. Arthington, Renee A. Rossini, Steven C. Flook, Sue E. Jackson, Moya Tomlinson and Craig S. Walton

PROCEEDINGS OF THE ROYAL SOCIETY OF QUEENSLAND VOLUME 126 2020

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Dedicated to the memory of Lynn Brake (24 August 1943 – 21 December 2019), tireless advocate for the springs of the Great Artesian Basin

Australian Government

Department of Agriculture, Water and the Environment

Griffith UNIVERSITY

Queensland, Australia

Australian Rivers Institute

Springs of the Great Artesian Basin has been produced with generous sponsorship support from the Australian Government Department of Agriculture, Water and the Environment, and financial contributions from the Queensland Department of Natural Resources, Mines and Energy and the Australian Rivers Institute, Griffith University. These contributions have enabled the Society to have the work typeset to a professional standard and to proceed from online open-access publication of the volume to print publication, giving the work a tangible presence and long archival life. Sponsorship support from the Department of Agriculture, Water and the Environment also enabled the Society to offer a Special Session on *Springs of the Great Artesian Basin* at the Australasian Groundwater Conference held in Brisbane in November 2019. The Royal Society sincerely thanks Mrs Kate Brake for advice and support during preparation of the volume, and all authors, reviewers and editors for their contributions to this Special Issue of the *Proceedings*.

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Patron
His Excellency the Governor of Queensland
the Honourable Paul de Jersey AC

FRONT COVER ILLUSTRATION
Thari-tharinha Spring near Kati-Thanda Lake Eyre, South Australia
Photographer and ©: Travis Gotch (date of photo 2005)

BACK COVER ILLUSTRATION
Thari-tharinha Spring near Kati-Thanda Lake Eyre, South Australia
Oil on canvas painting of the 2005 photograph of this spring
Artist and ©: Mark Keppel (date of painting 2017)

The painting was gifted to Lynn Brake on the occasion of a celebration of his life and outstanding contributions to the sustainable management of the Great Artesian Basin (GAB), the Lake Eyre Basin and his beloved GAB springs.

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GOVERNOR OF QUEENSLAND

Message from the Governor of Queensland

The massive and ancient waters of the Great Artesian Basin are one of the most awe-inspiring features of our natural geography. They sustained countless generations of the first Australians, and today furnish the essential water supply for many rural communities.

The Basin is also one of the largest natural reservoirs in the world, yet many aspects of its hydrology and geology remain mysterious.

This Special Issue of the Proceedings of the Royal Society of Queensland on the Springs of the Great Artesian Basin is an important contribution to our understanding of this magnificent natural phenomenon. It spans historic and contemporary narratives, Indigenous perspectives, scientific papers and opinion on the management, conservation and governance of the Basin. This diversity of content is faithful to the essential character of the Royal Society: multidisciplinary in nature and inclusive of both expert and lay perspective, unified by respect for intellectual inquiry and the advancement of human understanding.

Government House is the proud custodian of issues of the Proceedings of the Royal Society of Queensland going back many decades. This Special Issue is a fine addition to the collection, and as Governor and Patron, I commend it to the widest possible readership.

Paul de Jersey

His Excellency the Honourable Paul de Jersey AC
Governor of Queensland

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2020 *A Rangelands Dialogue: Towards a sustainable future* (Vol. 127)

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FOREWORD

The Royal Society of Queensland and its predecessor the Queensland Philosophical Society have been publishing the results of scientific and natural history investigations since 1859. From 1884, a nearly annual issue of the *Proceedings* has been supplemented from time to time with Special Issues on specific themes. This volume follows that tradition.

When Professor Angela Arthington of Griffith University and Dr Renee Rossini of the University of Queensland approached the Society with an offer to assemble scholarly papers relating to springs of the Great Artesian Basin (GAB), the Society's Council did not hesitate to endorse the proposal. We are delighted that Professor Arthington and her editorial team have been able to fulfil this commitment and bring this fine collection of papers to maturity.

This volume of papers on GAB springs, their groundwater-dependent ecosystems and the challenges of management and conservation is especially timely. Two decades have passed since formal listing in 2001 of 'The community of native species dependent on natural discharge of groundwater from the Great Artesian Basin' as endangered under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). The 2010 Recovery Plan for this community of native species provided a platform to galvanise action on issues of special significance to the management and conservation of springs and their communities of rare and endangered species.

Papers in this Special Issue – 19 in total including introduction and synthesis papers by the editors – contribute to these broad objectives from a wide range of sectors, individuals and perspectives.

I can attest to the painstaking attention that editors, authors, reviewers and others involved give to their roles, by reading manuscripts word by word, fixing typos, clarifying ambiguities, hunting for mistakes.

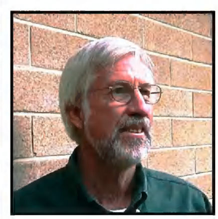
The Society is immensely grateful for generous sponsorship support from the Australian Government Department of Agriculture, Water and the Environment, and financial contributions from the Queensland Department of Natural Resources, Mines and Energy, and the Australian Rivers Institute, Griffith University. These contributions have enabled the Society to have the work typeset to a professional standard and to proceed from online open-access publication of the volume to print publication. The support from these bodies is evidence that scholarship is valued and that the contributions of the authors, reviewers and editors have resulted in a permanent addition to human knowledge.

Dr Ross Hynes
President

The Royal Society of Queensland acknowledges the First Peoples of the Great Artesian Basin, their long custodianship and inherent connection to the Basin and its springs, soaks, shallow aquifers, deep ancient waters and Country. We pay respect to the knowledge and cultural values of First Peoples of Australia and acknowledge Elders past, present and future.

This acknowledgment was crafted especially for *Springs of the Great Artesian Basin* by author Bradley Moggridge and editor Angela Arthington.

This Special Issue of the *Proceedings of The Royal Society of Queensland* is dedicated to the memory of scientist, teacher and advocate Lynn Brake (24 August 1943 – 21 December 2019), who worked tirelessly to foster sustainable management of the Great Artesian Basin's springs and groundwater-dependent ecosystems.



CONTENTS

Springs of the Great Artesian Basin – Oases of Life in Australia's Arid and Semi-arid Interior

Angela H. Arthington[1], Sue E. Jackson[1], Moya Tomlinson[1], Craig S. Walton[2], Renee A. Rossini[3], and Steven C. Flook[4]

Abstract

Springs of the Great Artesian Basin (GAB) are among the most revered, structurally complex, ecologically diverse and threatened groundwater-dependent ecosystems in Australia. In 2018, the Council of The Royal Society of Queensland recognised the need for consolidated knowledge to support evidence-based management and conservation of these unique, endangered ecosystems. Recent developments make this Special Issue of papers on GAB springs, their cultural values, endemic biota, and the challenges of management and conservation, especially timely. Two decades have passed since formal listing in 2001 of "The community of native species dependent on natural discharge of groundwater from the Great Artesian Basin" as endangered under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act, 1999). This formal designation was followed by the preparation of the Recovery Plan for the GAB endangered community. Similarly, two decades have passed since the publication of the original national strategic management plan for the basin. These two national initiatives are now being renewed with greater vigour and focus on the importance of saving water, a major factor in improving spring health. Papers in the Special Issue contribute to the broad objectives of the Recovery Plan and the Great Artesian Basin Sustainability Initiative from a range of sectors, individuals and perspectives. We anticipate that papers in this volume will stimulate new research, novel insights across all forms of expertise, and greater commitment to the wise use and protection of these miraculous oases of life and cultural history in Australia's Great Artesian Basin.

Keywords: Great Artesian Basin, springs, hydrogeology, groundwater-dependent ecosystems, endemic species, cultural history and values, stewardship and governance models, conservation and management frameworks

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Introduction

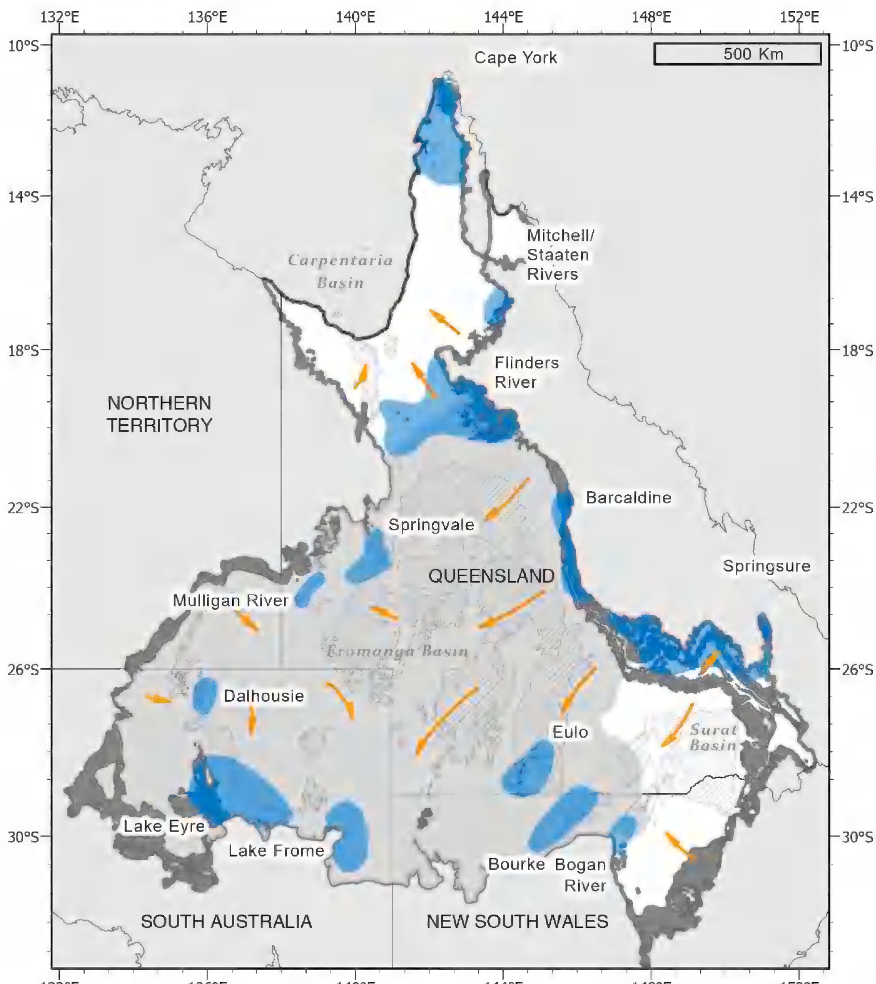
Beneath some of the most arid areas of the world's driest inhabited continent lies a vast reservoir of subterranean water – the Australian Great Artesian Basin (GAB). This ancient groundwater resource is one of the world's largest and one of the few that is still characterised by artesian conditions for large portions of the basin – where water may discharge to surface under hydrostatic pressure. The basin covers about 22% of the Australian mainland, including large areas of Queensland, New South Wales, South Australia and the Northern Territory.

Some of its waters date from the Pleistocene up to 2.5 million years ago. Modern recharge, from infiltration of rainfall around the eastern and western margins and from episodic river flows, is significantly less than discharge (Smerdon et al., 2012).

The GAB is a multilayered aquifer system, comprising a geological sequence of aquifers – water-bearing formations – and aquitards, which limit the movement of groundwater. The groundwater system is predominantly recharged where aquifers are exposed to the surface, along the eastern and western margins of the GAB (Habermehl, 2020). Groundwater flow directions are complex, particularly around the periphery of the basin where local groundwater flow directions can differ substantially from the regional trend.

In some locations, the GAB waters rise to the surface under hydrostatic pressure through geological faults and folds in the strata that overlie the aquifer (Figure 1).

Figure 1. The GAB with sub-basins, major regional clusters of springs (spring supergroups, shown in blue) (Fensham & Fairfax, 2003), local (hatch) and regional recharge areas (dark grey around the GAB periphery), regional flow directions (orange arrows) (Ransley et al., 2015). Source: Flook et al. (2020).



These natural discharge points form vents, seepages and more discrete waterbodies of astonishing variety – the GAB springs. Some springs form bubbling pools no larger than a paddling pool (e.g. Blanche Cup and The Bubbler in Wabma Kadarbu Mound Springs Conservation Park on the Oodnadatta Track, South Australia). The bubbling water represents the convulsions of the dying Rainbow Serpent after an altercation with a Kuyani ancestor (Friends of Mound Springs, https://www.friendsofmoundsprings.org.au/featured-mound/bubbler-and-blanche-cup/). At Edgbaston Reserve, north-east of Longreach in Central Queensland, there are 100 individual springs, but many of them form little more than damp areas and ankle-deep wetlands. Yet some Edgbaston (*Byarri*) springs are just deep enough to support one of Australia's most remarkable and critically endangered fish species (Fairfax et al., 2007; Kerezsy, 2020). The largest GAB springs are longer than 100 m and deeper than 3 m. At Dalhousie Springs (Witjira National Park, South Australia), large, deep, warm waters form the natural Dalhousie 'swimming pool' (Zeidler & Ponder, 1989). Throughout this volume, original photographs of these and many other GAB springs offer a window on their features and remarkable variety.

Due to the geographic extent of the GAB, these oases of life are found across arid, semi-arid and northern tropical landscapes (Figure 1), but the majority, and certainly the most well-researched springs, are located in the more arid areas of these landscapes. Originally, 11 groups of springs were identified (Habermehl, 1982), and later defined as supergroups by Ponder (1986). Subsequently, the two most northern groups were recognised and most maps show the 13 supergroups named in Figure 1.

Ponder (1986) proposed the basic spring terminology, ranging from the different parts and vents of individual springs, to the association of springs in groups, to spring complexes and, ultimately, the large groups of springs known as supergroups (Figure 1). Spring groups are also commonly based on the hydrostatic conditions under which they occur. Artesian springs are those which are fed by a deeper aquifer, with water travelling upwards through an overlying aquitard to reach the surface. Recharge or outcrop springs are those that are fed by a local groundwater system, with water travelling only a short distance through an unconfined aquifer at outcrop.

Australia's GAB springs offer a unique focal point for the intersection of many types of knowledge. There is the knowledge Aboriginal Peoples generated over thousands of years of living close to springs, passed down through origin stories, and expressed today in continuing cultural practices and stewardship. Colonial impressions and understandings obtained from early exploration, pastoral settlement and expansion also represent a source of knowledge of GAB springs, and testify to the heritage significance of springs. As Australian society grew more aware of the value of groundwater last century, technical knowledge of spring hydrogeology, ecohydrology and biodiversity also expanded (e.g. Ponder et al., 1989). Springs came to be recognised and regulated as groundwater-dependent ecosystems of great cultural, ecological, socio-economic and conservation significance, as concern about threatening processes grew and attention turned to ways in which society could more carefully monitor and manage springs. Reducing the sheer waste of groundwater from the GAB has motivated many of those committed to sustainable management over recent decades.

This compilation of papers on springs of the Great Artesian Basin is one of a long line of Special Issues of the *Proceedings of The Royal Society of Queensland*, devoted to themes of particular interest, and often with a regional focus. In 2018, the Council of the Royal Society recognised the need for consolidated knowledge to support evidence-based management and conservation of these unique, endangered groundwater-dependent ecosystems. Unlike previous special editions, however, the size of the basin means that the experience of authors and scope of the papers fittingly reach beyond Queensland state borders. Under the guidance of Dr Renee Rossini, a recent doctoral graduate with a passion for spring invertebrates (Rossini et al., 2018), the GAB springs project was duly launched in August 2018. A dedicated editorial panel came together to guide the formal call for papers, their review by independent experts, editing, cross-checking and final collation into Volume 126 of the Royal Society's *Proceedings*.

Recent developments make this volume of papers on GAB springs, their groundwater-dependent

ecosystems and the challenges of management and conservation especially timely. Two decades have passed since formal listing in 2001 of "The community of native species dependent on natural discharge of groundwater from the Great Artesian Basin" as endangered under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act, 1999). This formal designation was followed by the preparation of the Recovery Plan for the GAB endangered community (Fensham et al., 2010). It provided a platform to galvanise action on issues of special significance to the management and conservation of springs and their communities of rare and endangered species. The bold objective of the Recovery Plan is to maintain or enhance groundwater supplies to GAB discharge spring wetlands, maintain or increase spring wetland habitat area and ecological health, and increase populations of all endemic organisms.

Similarly, two decades have passed since the publication of the original national strategic management plan for the basin (GABCC, 2000). Importantly, activities geared towards drafting the national plan resulted in the first nationally coordinated basin infrastructure funding program, the Great Artesian Basin Sustainability Initiative (GABSI), commencing in 1999. These two national initiatives are now being renewed with greater vigour and focus on the importance of saving water, a major factor in improving spring health.

Papers in the Special Issue contribute to the broad objectives of the Recovery Plan and the Great Artesian Basin Sustainability Initiative from a range of sectors, individuals and perspectives. In this introductory paper, we place each contribution in context but defer a synthesis of knowledge gaps and future directions for research, management and conservation of GAB springs until the final paper of the volume (Rossini et al., 2020).

The Special Issue begins with an account of the importance of groundwater to Australian Aboriginal people, by Moggridge (2020) who researched this theme for his Masters thesis. In the beginning – the Dreamtime – springs were created by Aboriginal cultural heroes and revered as reliable watering points in harsh desert country, serving as sites of ceremony, oral instruction and settlements along major trade networks (Ah Chee, 2002; Harris, 2002). Rituals and ethics of caring for the land, water and all living beings illuminate our understanding of Aboriginal knowledge and affirm our profound cultural inheritance as new Australians. This awareness comes with an obligation to enter into respectful partnerships that aid recovery and restoration of Aboriginal practices and knowledge of spring country. Yet the cultural significance of many GAB springs, and the tacit knowledge held by Aboriginal Peoples from a vast area of Australia, remains poorly documented even after a recent surge in interest from scientists and water managers (Brake, 2020; Peck, 2020; Pointon & Rossini, 2020; Silcock et al., 2020).

In the time since European settlement, studies dating back over 140 years testify to the dedication of individuals and agencies committed to documenting, researching and monitoring springs. Papers in this volume provide comprehensive reviews of the hydrogeology and hydrochemistry of GAB springs, their modes of origin, the geography and biophysical attributes of springs, and understanding of processes needed to inform management and recovery of GAB springs affected by groundwater use and drawdown (Habermehl, 2020; Flook et al., 2020; Keppel et al., 2020). Recent surveys are still yielding new information in the less well-studied parts of the GAB, such as the Mulligan River Springs (Silcock et al., 2020), the only permanent surface water in this dry area on the edge of the Simpson Desert in far-western Queensland (Figure 1).

Discharge springs form oases of life extending in an arc around the margins of the GAB, primarily in arid and semi-arid landscapes. These patchy and largely isolated groundwater-dependent ecosystems differ from the surface-water wetlands of overlying catchments such as the Lake Eyre Basin. In these 'boom and bust' ecosystems, riverine freshwater species usually flourish during wet times but cling to life in ecological refuges during drier times. In these systems, aquatic species generally have wide distributions and excellent dispersal capabilities, allowing them to erupt from the disconnected waterholes that were their refuges during drought (Bunn et al., 2006). Although existing in the same landscapes, GAB springs create very different habitats for aquatic life. They form isolated islands of wetland in a sea of arid land, are rarely connected, relatively environmentally stable and hydrochemically unique (Ponder, 1995). While

springs are often utilised by surface-water species, GAB springs are exceptional in the high proportion of species that are endemic to these groundwater-dependent ecosystems (Fensham et al., 2011). They function as evolutionary refugia – permanent or semi-permanent groundwater-dependent habitats supporting rare and endemic species of plants and animals adapted over millennia (Davis et al., 2013; Murphy et al., 2015). Many species are restricted to a single spring complex (Rossini et al., 2018).

Five papers in this volume enrich our understanding of the patchy distribution patterns, special habitat requirements and conservation status of invertebrates and fish found nowhere else but GAB springs (Choy, 2020; Clifford et al., 2020; Kerezsy, 2020a,b; Rossini, 2020). The patterns of endemism they describe are especially interesting and of central relevance to setting conservation priorities for springs of the basin (Fensham & Price, 2004; Fensham et al., 2011).

Over the past century, development of the water resources and landscapes of the GAB has seen many changes and growing threats to springs and their endemic biota, as well as to the relationships that Aboriginal Peoples maintain with springs. Threats identified in the Recovery Plan include: aquifer drawdown; excavation of springs; stock and feral animal disturbance; alien (introduced exotic) species of plants and animals; tourist visitation; and development of impoundments (Fensham et al., 2010). Papers in this compendium address some of the more prominent threats and lay a foundation for reviews of progress towards threat abatement, effective management strategies and more effective conservation mechanisms. Flook et al. (2020) demonstrate how detailed hydrogeological conceptualisation and an understanding of the spring wetland water balance underpin monitoring strategies to enhance the detection of impacts of groundwater drawdown on spring wetlands.

The discovery in the 1880s that settlers could dig wells and drill bores to exploit the artesian water that fed springs was pivotal for the early pastoral industry. By 1915 more than 1500 artesian bores had been drilled into the GAB to provide flowing artesian water, and a vast system of open artificial channels, known as bore drains, was constructed to distribute flowing water to individual and grouped properties, often over significant distances (Brake et al., 2020). The benefits for travellers, settlements and the growing pastoral industry were enormous, but within 40 years grave concerns were emerging about declining bore pressure, huge water losses via evaporation and seepage (up to 80–95% wastage, Mudd, 2000; Noble et al., 1998) and adverse effects on springs. Brake (2020) describes this history and the implementation of the Great Artesian Basin Sustainability Initiative (GABSI) and progenitor programs, centred on artesian pressure recovery, sustaining GAB spring flows, and assisting landholders in the rehabilitation of bores and water delivery infrastructure.

The ecological consequences of aquifer drawdown on GAB springs and their resident biota have been severe in many spring complexes, undoubtedly resulting in loss of endemic species in some areas of the basin (Fairfax & Fensham, 2002; Fensham et al., 2010). Furthermore, hydrological and habitat changes associated with groundwater drawdown can greatly increase the vulnerability of springs and their biota to other threatening processes (Nevill et al., 2010).

Direct human modifications (excavation, impoundment) and patterns of surrounding land use have threatened the persistence and ecological health of numerous springs (Kennard et al., 2016; Rossini et al., 2018). As sources of water and food for livestock and feral grazers, many springs and their biota have been severely disturbed, especially during dry periods (Kodric-Brown & Brown, 2007). The establishment of alien aquatic species (plants, fish and amphibians) places further pressure on springs affected by drawdown and loss of aquatic habitat. Climate variability and future projections of a warmer and drier regime imply impacts on both recharge of the GAB and demands on the resource (Fu et al., 2020).

Alien aquatic species present particularly challenging management problems (Kerezsy, 2020a). The alien eastern gambusia (*Gambusia holbrooki*), a small live-bearing fish first introduced to Australia for control of larval mosquitoes, now threatens the persistence of the critically endangered red-finned blue-eye (*Scaturiginichthys vermeilipinnis*) in several springs at Edgbaston Reserve in the Aramac district of central western Queensland (Kerezsy & Fensham, 2013). Another alien pest, the cane toad (*Rhinella marina*) also threatens the conservation

of desert spring ecosystems by consuming endemic aquatic invertebrates (Clifford, et al., 2020). The occurrence of both pest species in springs at Edgbaston (*Byarri*), a precious cultural and conservation reserve (Ponder et al., 2010), is particularly worrying.

Disturbance and total grazing pressure from stock, feral species and native animals can seriously damage spring habitats and vegetation. De-stocking, and fencing around GAB springs to exclude stock and feral animals, are well-established management approaches, with early efforts dating back decades. The paper by Peck (2020) evaluates the management effectiveness of exclusion fences around springs in Currawinya National Park (south-western Queensland) using qualitative and quantitative condition assessment tools. Threat mitigation like fencing does not always result in a predictable or ecologically positive outcome. Total exclusion of all grazing through fencing can result in over-proliferation of native species such as the common reed (*Phragmites australis*) and *Fimbristylis* spp. Lewis & Packer (2020) present a remarkable 35 years of observational data on the response of *P. australis* and other wetland vegetation in GAB springs following stock exclusion.

Although discussions of spring management and conservation actions in this Special Issue focus heavily on the role of policy and basin-scale initiatives, several contributions remind us of the powerful role of citizens in understanding threats and protecting springs. Harris (2020) describes five decades of 'watching mound springs' through professional activities and engagement with many key scientists and Aboriginal custodians of South Australia's mound springs. He recalls the interest and controversy surrounding the Olympic Dam Mine project developed to mine world-ranking quantities of copper, uranium, silver, gold and rare earth elements. Later in life he formed the community group Friends of Mound Springs (FOMS). As Founding President, Harris has generated a huge following of friends devoted to protecting springs and saving threatened species.

Edgbaston (*Byarri*) and its conservation programs are shining examples of how the FOMS legacy is growing and expanding. The professional conservation experiments of not-for-profit conservation group Bush Heritage Australia have been supported by volunteers brought together to work with a shared passion to save endangered species and conserve the spring wetlands on which they depend (Kerezsy, 2020a,b; Kerezsy & Fensham, 2013).

Despite the unique hydrogeological character of GAB springs, their many endemic species and the severity of the threats they continue to face, these groundwater-dependent ecosystems have only recently attracted formal conservation attention. The "community of native species dependent on natural discharge of groundwater from the Great Artesian Basin" was listed as endangered and protected under Australia's main environmental legislation in 2001, under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act, 1999), and the 2013 EPBC Act amendment (the "Water Trigger") establishes water resources as a "matter of national environmental significance" (MNES) in relation to coal seam gas and large coal mining developments.

Pointon & Rossini (2020) review the relative strength, complexities and limitations within this system of legal protections as it applies to the conservation of GAB spring species and the particular features of their biological communities. They do so in broad terms relevant to the whole GAB, and in a case study of the Doongmabulla Springs (Central Queensland), which are not GAB springs, in relation to development of a major coal mine in their vicinity.

The twin themes of conservation and management bring this Special Issue to a close with papers offering principles, practical procedures and governance models to ensure the future of GAB springs and their endemic biological systems. Lewis & Harris (2020) propose a GAB springs conservation program and governance framework for South Australia. While not directly transferable to other jurisdictions, this program sets out important framing elements based around robust data systems, identification of priorities for conservation, Indigenous engagement, incentives for landholders, initial protection works, ongoing maintenance of protective measures, and an underpinning regulatory framework.

The final paper by Jensen et al. (2020) describes the GAB Springs Adaptive Management Plan (Brake

et al., 2020), designed to secure Lynn Brake's vision – shared by so many others – to achieve long-term and well-funded care and protection of springs. The multi-agency and multi-jurisdictional project was managed by Natural Resources SA Arid Lands, and funded by the (then) Australian Government Department of Agriculture, and by South Australian, New South Wales, Queensland and Northern Territory jurisdictions. The GAB Adaptive Management Plan and Template presents evidence-based methodologies to assess and manage risks to spring groups across the GAB while minimising disruption to current users of basin water resources.

As always with Special Issues, many important gaps in knowledge and ideas for further research have emerged in the papers themselves and from the critiques and commentaries of reviewers. To conclude this volume we offer a synthesis of knowledge gaps and future directions for research, management and conservation of GAB springs (Rossini et al., 2020). We hope this collection of papers and our synthesis will encourage deeper appreciation of the cultural, historical, ecological and economic significance of GAB springs (and springs with other groundwater dependencies throughout Australia), by offering new insights and enlightened strategies to protect and manage them. We anticipate that papers in this volume will stimulate new research, novel insights across all forms of expertise, and greater commitment to the wise use and protection of these miraculous oases of life and cultural history in Australia's Great Artesian Basin.

Acknowledgements

We gratefully acknowledge sponsorship support from the Australian Government Department of Agriculture, Water and the Environment; Queensland's Department of Natural Resources, Mines and Energy; and Griffith University. Their generosity has enabled professional typesetting and printing of the entire volume. Support from the Department of Agriculture, Water and the Environment also allowed the Royal Society to convene a specialist session on GAB springs at the Australasian Groundwater Conference held in Brisbane in November 2019. We sincerely thank the authors of papers in this Special Issue for their contributions, the reviewers of each paper for their critiques and commentary, and Sunset Publishing Services for quality proofreading and typesetting of the volume. Enthusiastic commitments of expertise, time and energy during the difficult months of the coronavirus (COVID-19) crisis are deeply appreciated. Special thanks are due to the Royal Society's immediate Past President Dr Geoff Edwards and Council members whose enthusiasm for the project and support made the publication of this Special Issue possible and rewarding.

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Craig Walton is a senior policy officer in the Queensland Department of Natural Resources, Mines and Energy. His role is focused on water policy in the Great Artesian Basin; and with a background in plant ecology, Craig is pleased to be overseeing policies and programs targeted at making the basin in Queensland watertight, because of the important ecological and social outcomes that will result from this work.

Steven Flook is Director of Management Strategies and Implementation, Office of Groundwater Impact Assessment, DNRME, Queensland. He is a passionate water resource professional with experience in water planning, cumulative impact assessment, groundwater-dependent ecosystems, science communication, design and implementation of research programs and inter-jurisdictional policy development. His experience relates predominately to investigations in the Great Artesian Basin and the Condamine Alluvium for the Queensland Government.

Aboriginal People and Groundwater

Bradley J. Moggridge[1]

Abstract

Aboriginal people have been part of the Australian landscape for 65,000 years or more, and in many areas, including the Great Artesian Basin, they have relied on groundwater for survival. Aboriginal people believe their story originated in the Dreamtime – the beginning, when Aboriginal cultural heroes created groundwater sites along with all other sacred sites. Their survival, particularly in a desert environment, has intrigued non-Aboriginal people for many years. While many studies have been conducted on how Aboriginal people survived at a local or regional level by accessing groundwater, no research has collated and reviewed the entire subject matter of 'Aboriginal People and Groundwater'. This paper, based on my 2005 Masters Thesis, endeavours to collate and review available research and provide an insight into the cultural relationships and dependence of Aboriginal people on groundwater. Since colonisation, the Australian continent, its landscape and the complex nature of Aboriginal society have changed. So too have human uses and reliance on groundwater, for it has become a favoured water supply for many communities and types of industry. In some cases, these uses have led to over-allocation and groundwater depletion or degradation. The future of groundwater use has to be managed sustainably, as Aboriginal people have done for thousands of years.

Keywords: Indigenous cultural values, Dreamtime stories, rainbow serpent, springs, sustainable management of groundwater

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Introduction

Groundwater is an integral part of the total water cycle and is necessary to sustain human and ecological life. Essentially, it is all the water below the ground surface stored in aquifers. Its volume greatly exceeds all other freshwater sources that are unfrozen. Considering this, groundwater contributes to a large portion of water supplies in Australia, where reliance on surface water may not be a viable option in a dry landscape. For instance, in Perth, Western Australia, groundwater contributes to approximately 40% of the city's water supply (Australian Water Association, 2005).

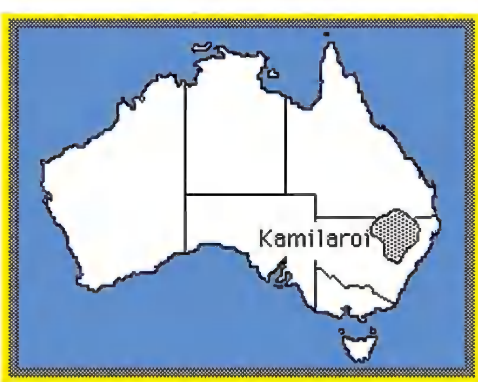
The occurrence of groundwater is dependent on local and/or regional geology, which can be complex. In Australia, aquifers can be classified into two types: confined aquifers and unconfined aquifers. Groundwater moves slowly through these aquifers – usually less than one metre per day – until it seeps into low-lying areas, streams, lakes, wetlands or the ocean. It can also be forced out due to gravity or hydrostatic pressure, to discharge along geologic fault lines. Unlike surface water, groundwater losses through evaporation are low and are buffered against climatic variability, especially drought. Groundwater is a vast resource with relatively constant chemistry and temperature.

Because groundwater has become a favoured water supply option for many population centres around Australia, many aquifers are over-allocated and authorities now need to consider sustainable groundwater extraction and use. This is the case for many of the New South Wales (NSW) major aquifers, with over-allocation as an outcome of past government policies (Gates & O'Keefe, 2002). Pollution also threatens the quality of groundwater.

Aboriginal communities are a part of the population centres that access groundwater for potable water. However, prior to European colonisation, Aboriginal people would have used groundwater sustainably and principally for survival; for them it was an infinite resource for thousands of years. Aboriginal water use is described in Lloyd (1988): "Australian Aborigines were exploiters, conservators, managers and manipulators of water resources. They were able to prevent the pollution of water, to filter it before drinking, to reticulate it, and to store it to reduce evaporation. Indeed, very little of the fundamental elements of hydrology and hydraulics eluded them."

At the time of my Masters Thesis (Moggridge, 2005), there had been limited localised, regional or state-wide studies on Aboriginal people and groundwater – a national review was required to fill this knowledge gap. To this end, all available written or recorded research, personal accounts, audiovisual materials, reports, journals, conference papers, art forms, oral histories and interviews with elders were accessed to document the relationships of Aboriginal people with groundwater. This paper covers groundwater stories from the Dreamtime, through art and oral history, early observations of Aboriginal people and how they obtained water, and finally how Aboriginal people use groundwater today. The topic was more than appealing to me as a Masters research project, being of Aboriginal heritage from the Kamilaroi nation in north-western NSW (Figure 1).

Figure 1. Location of the Kamilaroi nation (Source: Austin & Nathan, 1998). Available at https://www.dnathan.com/language/gamilaraay/dictionary/



Moreover, my country is situated at the lower limits of the Great Artesian Basin that was so important to my ancestors and is necessary for the ongoing survival of my nation today.

Aboriginal People in the Australian Landscape

Aboriginal people have been part of Australia's landscape for millennia. There is no exact date of when Aboriginal people first arrived on the Australian continent or satisfactory evidence to indicate they evolved in Australia, but estimates range from 40,000 to 65,000 years. Considering this, many Aboriginal nations believe that they have been here since time began – since the Dreamtime "when the ancestral heroes first appeared and began their epic journey across the land" (Isaacs, 1984), and began creating the land, sky, water and life.

Since Aboriginal people have been a part of Australia's landscape, they have experienced and effected numerous changes to its environment: for instance, changes in flora and fauna, ecological communities, fire dependence, volcanic activity, climate, and water availability. The biggest change to the Aboriginal environment would have to be the invasion and settlement of Europeans and consequent rapid deterioration of their homelands.

Throughout all of these changes, Aboriginal people have adapted and survived. Their survival would not be possible without the knowledge of how to find and manage water – without water there is no life. Groundwater sources played a significant role in their survival, especially in the desert regions, which cover approximately 70% of the continent.

Aboriginal Groundwater Resources

Several groundwater-related water sources that Aboriginal people have used in the past, and still use today, will be described in this paper. However, to each Aboriginal tribe, their names and significance would differ. These resources include: soaks/soakages or native wells, springs, mound springs, bores and hanging swamps.

Soaks/soakage or native wells refer to places where groundwater discharges to the ground surface. Landform and vegetation are key indicators. They can occur near rivers, in ephemeral riverbeds and sand hills, and near salt lakes. Native wells are

simply the traditional means of tapping these soaks (Kavanagh, 1984), and were thus dug in areas where soakages were known. According to Bayly's study, they ranged in depth up to 7 metres but averaged 1.5 metres in depth; they were then filled with debris, sticks, sand, or had covers/caps placed on top of the wells to reduce evaporation and stop animals accessing them and fouling the water (Bayly, 1997). Bandler (2003) also mentions that some were curved in shape for protection from evaporation and were larger at the base to give greater capacity. Hercus & Clarke (1986) give a detailed description of nine wells in the Simpson Desert.

Springs are often confused with soakages, but Tweedie (cited in Kavanagh, 1984) explains that springs occur where impervious layers outcrop; the water table may be forced to the surface and water appears as a spring. Either gravitational or hydrostatic pressures force spring water to the surface.

Mound springs are geomorphic formations raised above the surrounding land surface, formed by a deposit of minerals and sediment brought up from the artesian aquifers or confining beds by water at certain natural discharge points (Great Artesian Basin Consultative Council, 2000).

Bores are structures drilled or dug below the surface to obtain water from an aquifer system (Murray-Darling Basin Commission, 1999).

Hanging swamps are another groundwater-dependent system that Aboriginal people would have used. Hanging swamps are shallow depressions on sloping rock faces on the edge of predominantly sandstone cliffs and occur at moderate to high altitudes. They are a constant source of water, fed by rain and groundwater, thus allowing a range of plant species which, combined, attract animal species.

Aboriginal People and Mound Springs

Studies on Aboriginal people and mound springs have involved archaeologists such as Lampert (1985) and Florek (1987), social scientists, mining enterprises (e.g. the Olympic Dam Project; SADEP, 1986) and governments, because springs hold great cultural and ecological significance.

Many stories of Aboriginal ancestral heroes are associated with mound springs and their placement along travel routes, and feature myths and spiritual significance. Mound springs are semi-permanent oases in the desert that have provided water for Aboriginal people for thousands of years and thus have a strong cultural significance. All individual springs and complexes are known to hold significance for Aboriginal people, and it is impossible in contemporary times to predict, with any confidence, that an individual mound spring does not have any particular significance due to similarities with other springs in an area (Noble et al., 1998, in Mudd, 1998). Hercus & Sutton (1985) emphasise that "the springs are considered so important that the large-scale deterioration of any group of springs would cause great distress to at least some Aboriginal people, whether their associations with the sites are direct or indirect".

A paper by Ah Chee (2002) discusses the significance and deterioration of the Dalhousie Springs to the Indigenous Southern Aranda people and the Irrwanyere Aboriginal Corporation. The Dalhousie Springs are situated on the edge of the Simpson Desert in northern South Australia. To the Aranda the springs are known as the Irrwanyere or 'the healing springs'. Following European settlement, the springs became 'sick' from poor land management practices by settlers, and now the local Aboriginal people are left with a legacy of degraded land. It must be so painful for the traditional owners of Dalhousie Springs and also for all other traditional owners to see their land destroyed and treated with little or no respect; and when it is destroyed, the landholder sells it or leaves it for the Aboriginal people to repair. McFarlane (2004) explains the difficulty non-Aboriginal people may have in understanding Aboriginal people's distress when the environment is polluted or damaged: "If one part is damaged or destroyed, all other parts are under pressure."

Groundwater and the Dreamtime

Storytelling is an integral part of life for Australian Aboriginal peoples. Stories are passed from one generation to another, usually by the elders of Aboriginal communities. The Dreaming or Dreamtime is an English translation of an Aboriginal concept. For example, three tribes of central Australia, the Pitjantjatjara, Arrernte and Adnyamathanha, use the terms 'Tjukurpa', 'Aldjerinya' and Nguthuna', respectively, whereas the Gamilaraay people refer to the Dreamtime as 'Burruguu'.

Aboriginal stories are told in detail and re-enacted in ceremonies that capture the imagination

of the young, primarily for education. These teaching styles have proven to be inspiring and powerful tools in presenting Dreamtime beliefs and cultural practices. Dreamtime stories depict the very basic part of a long and complex event. Stories covered include: the creation of the land and life, protocols and tribal lore, life and death, warfare, hunting, linking every creature and every feature of the landscape, male and female roles, as well as sacred and public affairs.

These are stories of the history and culture of Aboriginal people, handed down in this way since the beginning of time; they refer to all that is known and all that is understood. Many groundwater-related sites would be Dreaming sites because water that originates from below the ground would be deemed spiritually significant by Aboriginal people. The Dreaming significance of these sites, for instance, would link surface and sub-surface waters through cultural heroes. These sites would have been the focus of trade, dispute resolution between tribes, male initiation and marriage. To Aboriginal people, the stories of the Dreamtime represent the past, present and future.

The Rainbow Serpent

The Rainbow Serpent was a highly significant and powerful cultural hero of Australian Aboriginal Dreamtime. The author has a cultural connection to the Kamilaroi's cultural hero, *Gurria* or *Kurrea*.

The Rainbow Serpent was connected to many different Aboriginal tribes throughout Australia, had many different names, and usually took the form of a snake/serpent creature that linked the people to features in the landscape. Sites and stories associated with the Rainbow Serpent were, and still are, considered culturally significant to Aboriginal people.

Anthropologists have long appreciated the significance of the Rainbow Serpent. Radcliffe-Brown (1930) stated that the Rainbow Serpent story was perhaps "the most important of the mythology and that fuller knowledge of this is important to any attempt we may make to understand the Australian conception of nature".

The Rainbow Serpent had many different roles depending on the tribe. Some of its roles related to: fertility in women and the land, close association with medicine men and important ceremonies, protector of its people, land and the formation of features such as springs, rivers, lakes and lagoons, rain and flood events. The connection between the Rainbow Serpent and groundwater is of particular interest in this paper.

In western NSW there is deep connection between the Rainbow Serpent (*Wawi*) and both surface water and groundwater, connecting beneath and across landforms. In Rose et al. (2003), an account of this connection is given by Steve Meredith:

> This country was made by the ancestors. *Wawi* the Rainbow Serpent came up through the springs, he came from Nakabo springs, Ngilyitri country. Wherever he travelled he left ochre to show where he had been. The springs were entry and exit points. He came out of the earth, travelled along its surface, and then back into the earth. *Wawi* travels and is still there. We know he's still there.

Rose et al. (2003) further explain that in Ngiyampaa country the *Wawi* came from the east, travelling underground, coming up in a spring in the Manara Range (near Ivanhoe, NSW) where he had a fight with Robin Red Breast, which he lost and is now stuck in the rockhole. *Wawi* rises out and returns as the water in the rock hole rises and falls.

Tindale (1974) mentions how Walmadjari men in times of drought (*lalga*), go to a big permanent waterhole, remove excess sand or soil from the hole and add to the height of the walls, making the hole deeper. Then they shout out very loudly with special cries to tell the *Wanambi* or giant carpet snake that they need water and to come and fill the well for them. It is believed that the giant hidden snake yields the seeping water to the Walmadjari. From a hydrogeological interpretation, these Walmadjari men have dug into the saturated zone, thus allowing groundwater to seep into the hole.

The association between the giant carpet snake and permanent waterholes in desert regions is so close that, for instance, when a waterhole dries up it is believed the snake has died. Under tribal lore, if a person mistreats a waterhole that affects the snake, punishment is inevitable.

These lores and customs would have been a survival trait, specifically to protect the water quality

and quantity of waterholes. Zaar et al. (2002) provide examples: "... at some waterholes, in order to avoid contaminating the water, people are not allowed to put their hands in to scoop water out", so for hygiene purposes they drink by sipping the water without using their hands. A Traditional Owner – Tony Djakanawuy – talks of protecting a stream called Darrangay in Arnhem Land: "... upper pools were used for drinking and the downstream pool was used for swimming" (Zaar et al., 2002). Another example is discouraging children from playing in springs by stating a serpent or bad spirit will take them. These were simple ways to protect water quality.

The Rainbow Serpent is also culturally significant for the Baakantji people. Martin (2003) mentions a story that links a waterhole at Union Bend, Wilcannia (western NSW) with the *Ngatyi* or Rainbow Serpent. This site is part of a series of *Ngatyi* waterholes along the Darling River that are important to the Baakantji people.

Yu & Yu (2000) record how the Karajarri people (south-west of the Kimberley region, Western Australia) describe the Dreaming species: *Pulany* or water snakes and serpents which reside in or have created permanent water sources – *jila* (spring) or *pajalpi* (spring country). The presence of *Pulany* in a spring is often indicated by the *panyjin* reed (species unknown), and is a warning sign for children not to swim there. *Panyjin* reeds are said to be the whiskers of the *Pulany*. Strangers should not approach a *jila* without the presence of a countryman for that area, who will call out to warn the *Pulany* of their presence and state their relationship.

Groundwater Stories from the Dreamtime

My thesis records many stories that indicate the linkages between surface water, groundwater, lakes and rivers, cave systems, natural springs, thermal springs, rain events recharging the aquifers, and how in drought excess discharge allowed cultural heroes to move with water-table fluctuations. Here I have selected three Dreamtime stories about springs:

The Freshwater Springs at Raymanggirr

At Raymanggirr, a place on the northern coast of Arnhem Land somewhere near Lake Evell, the grandchildren of the old frill-necked lizard man were collecting honey. The frill-necked lizard heard, and stopped and listened. "Aha! My grandchildren are collecting honey!" He heard them chopping the tree to collect the wild sugarbag. "That tree's going to fall down," he said, and so he ran to a rocky point in the sea and looked up at the land. He named that point Mayawalpalnga and then he ran on.

Then his grandchildren called to him: "Come here, you dear old thing! You can have the top part of the honey in the tree, we'll have the bottom part." And they ate the honey. The lizard was eating his over there when he got something stuck in his throat. When we cook the frill-necked lizard, we still find these splinters in his throat. And he ran off into the bush calling, "A bit of the tree has stuck in my throat." He ran down to the edge of the sea water, into where the lily roots are. And here where the water runs into the sea, it is fresh. That old lizard man showed us where it is, and we can drink it today.

This is how the people collect it. They go down with a pannikin. When the tide's not full you can just collect it in a pannikin. But when the tide comes in and the spring is submerged, the water is collected in the mouth, sucked up into the mouth, and spat into a paperbark cup or pannikin. It's collected in the mouth. It is held in the mouth, carried over, and spat, and more is collected, and spat out, and more, and spat. Then it's carried to the camp and given to the people. "Sorry, not much water! The tide's in. Too much salt water. We'll go back later when we can dip for water properly."

If anyone objects to the spit, you can get a long hollow piece of wood like a bent didjeridu and the water will flow into it until it fills up. And another one, until that one fills up. Then carefully lift out the wood, and carry it to the camp and put it down. The water just flows by itself. When the tide's out, it runs down the beach. At Raymanggirr (Manuwa, Milingimbi, in Isaacs, 1980).

The Formation of Spring Waterholes in the Flinders Ranges

A family was walking from Curnamona to Barratta Springs. Because of dry weather there was no water and being so hot the family got thirsty. The old man told his family to walk

along slowly toward Mount Victor while he went to Barratta Springs to wait for a kangaroo. He wanted to kill it and make a waterbag out of its skin to carry the water back to his family, which by this time would have been somewhere near Mount Victor.

At Barratta Springs, the old man waited for the kangaroo which was coming from Murnpeowie. As the kangaroo hopped along, the old man could hear the thumping sounds. The next stop the kangaroo made was at Pepegoona Spring, near Wooltana Station. From there, the kangaroo hopped on to Nurowi Springs and made water. There was no water there, so he hopped onto Emu Bore, which is now an artesian bore. From Emu Bore, the kangaroo hopped on to Limestone. He couldn't find any water there so he had a rest. The white ground at Limestone represents where the kangaroo rested. He then hopped to Glenwarrick Springs and from there he started hopping towards Barratta, but on his way he saw a big snake which now represents Tooths Knob Hill on the Martin's Well property. He got frightened so he went around toward Kemps Dam. There was no water there, so the only place he had to go was to Barratta Springs.

When he got there, the old man killed him, got his skin and made it into a waterbag, filled it up with water and headed off towards Mount Victor to find his family. When he got to Mount Victor he saw his family lying on the ground. They were dying, so he quickly poured water on them. As he poured the water on them it spread and formed a swamp or a kind of a lake. When he saw them moving and starting to come around, he jumped into the middle of the water and he saw his family turning into ducks. He disappeared into the sky and formed the Morning Star.

His family couldn't find him, so they looked into the sky and yelled out, "Look up there! That's our father looking down at us." That is how the springs were formed from Pepegoona Spring in the north down the eastern side of the Flinders Ranges to Barratta Springs (Eileen McKenzie, Flinders Ranges, in Isaacs, 1980).

Arkaroo's Dreamtime Journey

Back in the Aboriginal Dreamtime, a giant serpent known as Arkaroo, who was living in the main water pound in the high Gammon Ranges south-west of Arkaroola, slithered down to the plains to quench his thirst. Arkaroo descended upon Lakes Frome and Callabonna and drank them both dry. The water was saline, and he became bloated. He dragged his heavily laden body back up towards the Gammons, and in doing so, he carved out the deep sinuous gorge that is now known as Arkaroola. On his way back he stopped at several places for a rest, and while doing so he formed springs and waterholes along the way. There are a few permanent ones around there now.

He dragged himself up into the Gammon Ranges, where he now sleeps safely in a hideaway at the Yacki Waterhole. Restlessly he sleeps on with his belly full of water, and whenever he turns the rumbling in his stomach sends out great noises that can be heard from time to time to this day. The minor earthquakes and rumblings have been recorded.

One of the most important waterholes left around these parts by the Arkaroo is that of the Paralana Hot Springs. The Aboriginals of long ago found this spring very convenient. They used to use it for domestic purposes, as well as bathe in it. It is said to have cured minor aches and pains. This spring became hot when, back in the old time, two young warriors fought for the love of a young girl. The victor, after killing his opponent, plunged his fire stick murder weapon deep into the spring, thus making it hot. Since then the water emerges only little below boiling point (May Wilton, in Isaacs, 1980).

Aboriginal Survival and Groundwater

The ability of Aboriginal people to survive in the Australian landscape, especially in desert regions engulfing approximately 70% of the continent, is somewhat astonishing. These regions of Australia undergo extreme variations such as low rainfall with high evaporation and large temperature variations between night and day.

Their ability to survive such conditions would not have happened in an instant; it would have developed over many thousands of years, when each aspect of knowledge gained by elders or tribespeople would have been passed down to the next generation. This suggests a highly developed

and sophisticated culture of teaching and learning, and the will to survive using all resources available.

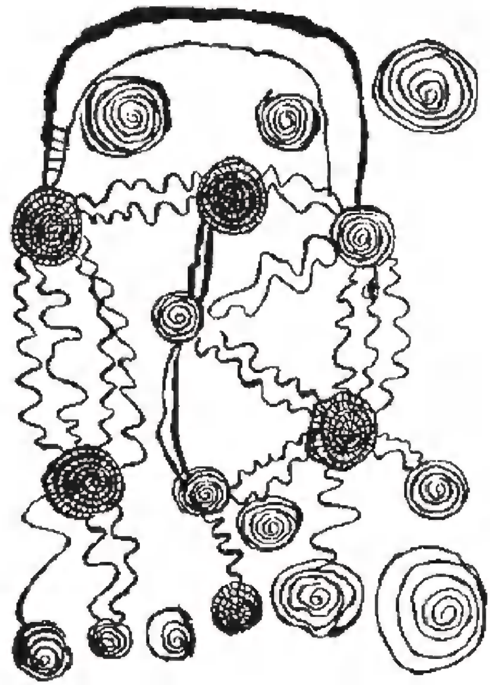
Aboriginal tribespeople developed a precise classification system for sites within their country. Their survival was dependent on this knowledge, and failure of this system would be fatal for the tribe. It was necessary to be precise when talking about waterholes, as life might depend on going to the right place at the right time (Lowe & Pike, 1990). A principal site for a tribe would have been a place to obtain water. Groundwater sources would have been significant, especially where waterbodies such as rivers or areas with high rainfall were not an option for water supply. Over thousands of years and to this day, Aboriginal people still know how to find or dig for water that has seeped up from subterranean sources.

The Walmadjari tribes' classification of water systems is given in Tindale (1974), and within this system groundwater sources are described as follows. They include waters trapped in deep sand which are classed as soak waters (*tju:mu*), and permanent waters classed as *tjila* and *tjaramara* which include natural springs (e.g. Joanna Springs in Mangala territory).

Another Aboriginal classification system for identifying groundwater sources through art is given in Figure 2 (Tindale, 1974). The drawing was done by Katabulka of the Ngadadjara tribe, who camped at Warupuju Soak in the Warburton Ranges, Western Australia. The original painting was four times as large and depicted in red and black. The painting depicts a map of water sources showing pools and soakages.

> Across the top of it Tjurtirango the rainbow lies, and between it are two concentric spirals representing Kalkakutjara, the "heavenly breasts" [*kalka*] nipple and [*kutjara*] two, which gave rain that flows into [*kapi*] or waters. These are the balance of the concentric spirals. Five darker ones possess mythical [*koneia*] carpet snakes therefore are considered never-failing; the others are temporary waters. Down the middle runs a stream bed, dry except during rain. On it are marked three waters, of which the top one is Warupuju. Zigzag lines from water to water are the tracks or native roads of men wandering in search of food (Tindale, 1974).

Figure 2. Drawing by Katabulka of the Ngadadjara tribe in the Warburton Ranges in Western Australia. *Tjurtirango*, the rainbow, yields water to storage wells, and sand soaks symbolised by concentric spirals. Tracks made by men join the various waters (Source: Tindale, 1974). Available at http://hdl.handle.net/1885/114913



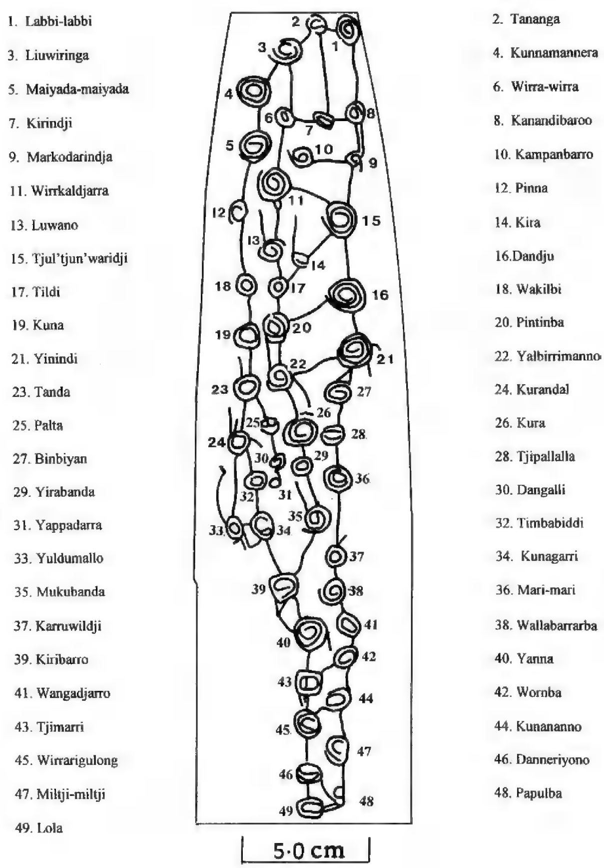
To find groundwater sources Aboriginal people would use all their available resources and natural indicators, which Tindale (1974) describes: "… in the arid zone, wild dingos preformed [*sic*] a service to Aboriginal people by locating and digging open water soakages." Following this, a digging stick would have been used to further dig out soakages to keep them clear of debris. Tindale (1974) also mentions the Nullarbor Plain where "a line of ants going down into a sinkhole in the limestone, can represent subterranean cave water" – karst groundwater.

Figure 3 is a reproduction of maps incised into spear-throwers, indicating the water resources of the Bindibu [=Pintupi] people of Great Sandy Desert, Western Australia. The narrative is given in Bayly (1999) and Brodie (2002) from the original description by Thomson (1962) at the end of his 1957 Bindibu [=Pintupi] Expedition when he

received the generous gift from Tjappanongo, who names and describes 49 water sources:

> Just before we left, the old men recited to me names of more than fifty waters – wells, rock-holes and claypans – including those that I have described in this narrative; this, in an area that the early explorers believed to be almost waterless, and where all but a few were, in 1957, still unknown to the white man. And on the eve of our going, Tjappanongo produced spear throwers, on the backs [of] which were designs deeply incised, more or less geometric in form. Sometimes with a stick, or with his finger, he would point to each well or rock hole in turn and recite its name, waiting for me to repeat it after him. Each time, the group of old men listened intently and grunted in approval – "Eh!" – or repeated the name again and listened once more. This process continued with the name of each water until they were satisfied with my pronunciation, when they would pass on to the next.
>
> I realized that here was the most important discovery of the expedition – that what Tjappanongo and the old men had shown me was really a map, highly conventionalized, like the work on a "message" or "letter" stick of the Aborigines, of the waters of the vast terrain over which the Bindibu hunted.

Figure 3. A highly conventionalised map of the Western Australian water resources of the Bindibu [= Pintupi], as carved into the back of a spear-thrower (Source: Redrawn from a photograph in Thomson (1962) by Bayly (1999)). Available at https://www.rswa.org.au/publications/Journal/82(1)/82(1)bayly.pdf



Numerous natural indicators would have guided Aboriginal people to groundwater. Some are mentioned above, but further indicators are extensively described in Kavanagh (1984), including the terrain, birdlife, vegetation, animals and insects. Considering these indicators, Aboriginal people then had to access the aquifer for the precious water. A prime example of Aboriginal ingenuity is given in Burnum Burnum (1988), where the activities of the Central Lakes people, situated east of the Western Desert, had constructed tunnel-reservoirs to access underground water in the same way settlers later tapped artesian bores. Bandler (2000) mentions the structures and various formations, some natural, others man-made, which show a high degree of expertise and knowledge in assessing and preserving precious groundwater. The works were an integral aspect of Aboriginal culture, carried out with simple tools, as pottery and metals had not been introduced.

Aboriginal Art and Groundwater

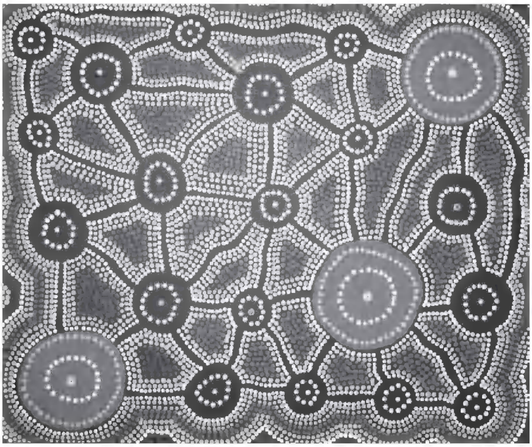
Aboriginal art has played a significant role in classifying, representing and describing significant groundwater sites for Aboriginal tribes, for knowledge of water sources is so important to a tribe's survival. Aboriginal art was not only painted on canvases or linen as modern society now demands, but earlier Aboriginal people used many media, such as the body for ceremonies, rock shelters and platforms, ground designs (sand drawings and ground mosaics, also used for ceremonies), implements or artefacts, ceremonial poles and the bark off a tree.

Aboriginal art, especially that originating from desert regions of Australia and in the dot art form such as the Warlpiri and Pintupi Language Groups (north-west of Alice Springs, Central Desert of Australia), will constantly make reference to and represent groundwater sources such as soakages and springs. Some good examples of desert art indicating groundwater sources (springs), along with explanations, are given in Stokes (1993).

Aboriginal art uses traditional symbols that can be read in many ways. Because of this, even the secret/sacred parts of a story can be painted but still protected, for the artist is the only person who fully understands the meaning (Stokes, 1993).

Three Waters, painted by the author (Figure 4), is a personal story that I dreamt about and consequently painted onto canvas. The story was later confirmed by Kamilaroi elders as representing three soakages within the ancestral country. The painting represents three significant groundwater sources – soakages (large circles) which ancestors utilised throughout time. They are hand dug and consequently maintained en route or when the ancestors passed these sites. The small dark circles are camp sites along their travels, and the dark lines joining them indicate the travel routes taken between camps and the soakages.

Figure 4. A photo of a painting titled Three Waters (acrylic on canvas, 60 cm × 50 cm) painted by the Kamilaroi author of this paper (Source: B. Moggridge (2002) from personal collection).



Aboriginal art is described as the oldest continuous tradition of art known. Caruana (1987) states that there is no known fixed notion of traditional Aboriginal art, for it is not a static relic of a bygone era but a vital and pertinent expression of current human concerns. Through their art, Aboriginal people celebrate the ancestral mythologies which form the basis of their lives and cultures.

Aboriginal People and Groundwater Today

Aboriginal people would have chosen their place of settlement primarily for cultural, survival and social reasons. Permanent Aboriginal settlements have now replaced the former nomadic lifestyle, with many communities consisting of over 1000 people. Most of these settlements are in remote locations and rely on groundwater tapped by bores; supplying water to these communities is an ongoing challenge. Yuen et al. (2002) record that the challenge for remote Indigenous communities in Australia is to provide adequate supplies of potable and non-potable water to achieve health outcomes and meet cultural needs while minimising the economic, social and environmental costs.

A report by the Human Rights and Equal Opportunity Commission (2001) mentions that the number of remote Indigenous communities has grown over the last 20 years, largely due to the outstation movement. Further to this, Rowse (1999) explains that Indigenous communities as we know them today are a legacy of settlements around food rationing stations or mission and reserve establishments. Settled mixes of different family, tribal and skin groupings are new, and many of the social issues arise from the new types of community living that have no traditional basis for Aboriginal people.

From personal experience, the land where Aboriginal people are forced to settle in NSW is usually land of low value, highly degraded, unfamiliar country (not traditional lands) or adjacent to the local council's activities such as waste management centres and sewage treatment plants (Moggridge, 2003).

The availability of water is a crucial decision affecting an individual and their community's quality of life, as the life of the author's grandmother (Brenda Benge née McGrady, 1918–2016) exemplifies. Nan was born in north-western NSW at Euraba Mission in 1918, and not long after her birth the whole community was moved to Old Toomelah. Then, in 1938, the community was forced to move again to the current Toomelah settlement situated on the banks of the Macintyre River. These moves came about because of a lack of potable water (B. Benge, pers. comm., 2002). The community currently uses a groundwater bore as their potable water supply.

Water availability and, in particular, permanency are often described as critical factors influencing the settlement patterns of Australian and other Indigenous peoples (Thorley, 2001). Water availability also pre-determines the distribution of plant and animal species. From an archaeological sense this is also reflected in the review of Thorley (2001) on water supplies and use in the Palmer River catchment, central Australia. This study displayed a close relationship between permanent waters and a wide variety of archaeological materials, whereas scatters near ephemeral waters were generally described as being less diverse. However, this pattern may vary around Australia, due to the significance of the water source to a particular tribe.

In desert regions, rainfall is unpredictable along with temperature extremes. The unpredictability of rainfall directs communities to groundwater for the main water supply (Gray-Gardner & Walker, 2002). A good example of groundwater's significance is given in Yu & Yu (1999), where a senior Karajarri man from the Great Sandy Desert, John Dudu, describes life without groundwater: "Water is the life for all of us. It's the main part. If that water go away, everything will die. That's the power of water. He connect with the land." Under their law, Karajarri are responsible for looking after their water; this would have been similar all through Aboriginal Australia.

Gray-Gardner & Walker (2002) indicate the total number of Aboriginal communities with a population of 100 or less using groundwater (Table 1). The discrete communities represented are concentrated in the more remote areas of the Kimberley and central desert regions and Arnhem Land.

Communities situated in remote areas using groundwater experience difficulties in securing access to bore water supplies of sufficient quality and quantity; also, the use of technology with regard to these supplies adds to the complexity of supplying infrastructure.

Table 1. Groundwater supplies for Indigenous communities with a population of 100 or less (Grey-Gardner & Walker, 2002).

State* or Territory	Number of communities	Number of communities on bore water	Per cent communities on bore water	Reported population in communities on bore water
Northern Territory	588	417	71%	8,226
New South Wales	35	6	15%	425
Tasmania	1			
Western Australia	235	182	78%	4,365
South Australia	90	47	52%	730
Queensland	109	22	20%	393
Total	**1,058****	**674**		**14,139**

* Victoria and the Australian Capital Territory do not have communities with a population of 100 or less.
** Six Northern Territory communities did not state their type of water supply.

Within Aboriginal communities there is a constant fluctuation in residency numbers as movement between large centres and country may be influenced by a number of factors:

- Schooling.
- Family, e.g. 'sorry business' (funerals).
- Ceremonial or cultural reasons.
- Business or political meetings.
- Sporting events.
- Medical.
- Shopping.

These fluctuations in community numbers will place a strain on the community's infrastructure, i.e. water supply and wastewater disposal. It is integral for service providers to understand the cultural obligations of Aboriginal people (which differ from region to region). Planning the infrastructure for communities, depending on the cultural activity, can decrease a settlement to zero for up to six months, or the population may double for periods of time. Therefore, peak loads and demand will vary and the appropriate systems have to be in place to accommodate these patterns.

Studies of Groundwater Supplies and Services to Aboriginal Communities

Several studies have been carried out on Aboriginal communities in remote or desert country where community health and social issues are evident and service provisions are poor, especially regarding potable water from groundwater sources. These studies have reviewed sustainability, social disadvantage, service provision, water quality and quantity, usage and management.

Review of the 1994 Water Report

In 1994, the Federal Race Discrimination Commissioner (RDC) released the Water Report, containing the findings of a comprehensive inquiry into the provision of water and sanitation services to Australia's remote Indigenous communities. A review of the 1994 Water Report was conducted by the Human Rights and Equal Opportunity Commission (2001) to assess developments over the past five years in 10 Aboriginal communities from around Australia between 1994 and 1999. The Centre for Appropriate Technology (CAT) in Alice Springs carried out the review for the Commission.

The 10 communities included: Punmu and Coonana from Western Australia, Yalata and Oak Valley/Maralinga from South Australia, Mpweringe-Arnapipe from the Northern Territory, Dareton and Tingha from New South Wales, Doomadgee from Queensland and two islands in the Torres Strait – Boigu Island and Coconut Island.

The Review documented significant improvements in water supply, with most communities accessing groundwater. However, communities still depend on an ongoing role of the state agency or regional service provider.

Western Water Study

The Western Water Study 1994–1997 was a groundwater study carried out by the Australian Geological Survey Organisation (AGSO) and partners (Central Land Council, the Northern Territory Department of Lands, Planning and Environment, and the Aboriginal and Torres Strait Islanders Commission – ATSIC). A summary of this study and its findings was given in Human Rights and Equal Opportunity Commission (2001).

The study area covered 68,000 square kilometres of central Australia. The main objectives of the study were to:

- improve access to groundwater information for Aboriginal people on their land;
- enhance environmental health;
- ensure equity in access to acceptable safe water, especially in remote and arid areas; and
- develop a rapid methodology that will provide these objectives.

Following evaluation, the study produced:

- a geographic information system (GIS) comprising: geological, hydrological and other pertinent data relating to water and the environment;
- a CD-ROM with all GIS information on water for the community to access and make decisions;
- a positive consultation and discussion process with the Aboriginal communities involved; and
- a 22-minute video recording produced by AGSO, which describes the study 'Water from Stone, Kapi mantanguru apurungu pakantja'.

Community Water Supplies in the Anangu Pitjantjatjara Lands

This study investigated the sustainability of nine major community water supplies in the Anangu Pitjantjatjara Lands, South Australia, between 1997 and 1999; the report was compiled by Dodds (2001). Groundwater derived from the 150 production bores is the only source of reticulated water in the Anangu Pitjantjatjara Lands, with many stakeholders involved in the study. Results from the Fitzgerald et al. (1999) report are summarised here.

The groundwater supply is derived from fractured rock aquifers, which are discontinuous and limited in extent. Each community needs two bores with reasonable yields, and preferably three bores as a safeguard against bores drying up. Water quality is relatively good, with five of the nine satisfying Australian Drinking Water Guidelines and the remaining requiring treatment prior to consumption. Hardness of the Anangu Pitjantjatjara Lands groundwater is widespread.

The outcome of the project formed the scientific basis for the development of a regional water management strategy for the Anangu Pitjantjatjara Lands, with further consultation with communities as required. Eight recommendations listed below were produced by the study for relevant stakeholders to undertake (Fitzgerald et al., 1999):

1. The regional water management strategy should consider the scientific results reported here in conjunction with community aspirations and social, economic, political, and institutional factors. The responsibility for the strategy is likely to be with the new Arid Areas Catchment Water Management Board. The strategy should also consider likely water supply needs for economic development including pastoralism, mining or irrigation, also future needs for outstations.
2. We recommend that the bore monitoring program be continued for 10 years to provide the water use and water level data on which management of the borefields must be based and to determine the effect of recharge events of these groundwater systems.
3. The monitoring program needs some extension and changes: water level data is required for the borefields at the emerging communities of Watarru, Kanpi, and Nyapari; and some unpumped bores should now be monitored to obtain information on recharge without the complication of pumping (there are observation bores at Pukatja, Turkey Bore, and Iwantja available for this purpose). Creek flow should also be monitored with staff gauges in selected locations where groundwater recharge is dependent on creeks.

4. Water search leading to additional drilling is recommended for Mimili, Kalka, and Yunyarinyi (Kenmore Park) and is probably also needed at Watarru.
5. Water treatment (desalination) is recommended for community water supplies with unacceptable water quality such as those at Iwantja (Indulkana), Mimili, Amata and Kaltjiti.
6. Rainwater options should also be explored for the communities where groundwater quality is marginal to unacceptable. Rainwater can be a valuable source of drinking water, supplementing the supply of water from the bores. Stormwater harvesting, although probably less viable, should also be explored.
7. Our observations indicate the necessity of regular water quality monitoring especially for bacteria, and that appropriate field test kits are now available. The agency responsibilities for water quality monitoring need to be clarified.
8. Field trials of water conditioning of Amata carried out over 18 months appeared to successfully remove and prevent scale build-up in domestic installations. Use of this or similar units will reduce the high cost of maintenance and replacement of domestic hot water and other installations in these remote communities. There is a need for more extensive field trials of water treatment technologies for remote communities.

Summary and Conclusions

Groundwater is an integral component of the water cycle and classed as a finite resource – it is vast, travels through aquifers at a slow rate, and depends on local and/or regional geology. In Australia, it has become a favoured option for population centres as a potable water supply, but in some regions has been over-allocated, managed poorly and is now in danger of irreversible impacts. Careful forward planning by authorities is now required to avoid further groundwater depletion.

A vast number of Australian Aboriginal people and communities currently depend on groundwater but have a much longer history of use and connection (with timeframes of up to 65,000 years) compared to non-Aboriginal people. Their association with groundwater started in the beginning – the Dreamtime – and is still strong today, when it is accessed through traditional as well as contemporary means. Aboriginal people used all available groundwater resources sustainably.

This long association with groundwater has resulted in Dreamtime stories related to sites being created and then passed on from one generation to another. The stories are re-enacted in ceremonies that capture the imagination of all, for educating and thus surviving. Many stories relate to individual groundwater sites as they are each significant.

Most traditional Dreamtime stories were lost following colonisation, assimilation and forced separation from country, but some survived and were passed on by tribespeople. Early settlers and anthropologists recorded some of these stories.

The Rainbow Serpent is a prominent and powerful cultural hero in many Dreamtime stories, and these stories relate closely to groundwater sites. The Rainbow Serpent had many different roles and names across the landscape, but sites associated with it are considered culturally significant.

The ability of Aboriginal people to survive in the Australian landscape, and especially in desert regions, is somewhat remarkable. This ability was dependent on a knowledge system that was precise; if not, it could have been fatal for a tribe. Knowing where to find water sites was a high priority, and Aboriginal people used all resources and indicators available to them for identification. These included: natural indicators (animals, insects), knowledge of the landscape and seasons, oral traditions (stories), and of course art, which has become popular in modern times.

Over many thousands of years, Aboriginal people have accumulated a comprehensive and astounding knowledge of groundwater. Part of this knowledge extends to sustainable management and use of groundwater. These factors need to be taken into consideration by governments – local, state or national – when planning decisions are to be made that may affect the quality or quantity of groundwater. If we want Australia to protect our groundwater resources for future generations, Aboriginal people must be involved in planning and decision processes.

Today, many permanent Aboriginal communities access groundwater for potable supply. This lifestyle is somewhat different from the pre-colonisation

nomadic lifestyle, and supplying adequate water to these communities is a challenge, as explained by Yuen et al. (2002) above.

The few studies conducted to understand Aboriginal people and their use of groundwater have been at a local or regional level, mainly investigating groundwater quality and quantity. However, even fewer studies have looked at the close cultural relationship between Australian Aboriginal people and groundwater. This paper records the beginnings of my research on relationships, Dreamtime stories and cultural knowledge. My intention was, and still is, to inspire other Aboriginal people and researchers to take the subject matter further.

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Author Profile

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Hydrogeological Overview of Springs in the Great Artesian Basin

M. A. (Rien) Habermehl[1]

Abstract

The Great Artesian Basin (GAB) is a regional groundwater system consisting of aquifers and confining beds within the sedimentary Eromanga, Surat and Carpentaria Basins. They underlie arid to semi-arid regions across 1.7 million km^2, or one-fifth of the Australian continent. Artesian springs of the GAB are naturally occurring outlets of groundwater from the confined aquifers. Springs predominantly occur near the eastern recharge margins and the south-western and western discharge margins of the GAB. These zones of natural groundwater discharge represent areas of permanent water, with widely recognised cultural, spiritual and subsistence importance to Indigenous people for tens of thousands of years. The unique hydrogeological environments – discharge, hydrochemistry and substrate – support a range of endemic flora and fauna protected under the EPBC Act (1999). Springs have formed in many areas across the GAB; however, the largest concentrations occur near the south-western margins of the basin. Supporting these flowing artesian springs is a multi-layered aquifer system, comprising Jurassic- to Cretaceous-age sandstones and siltstone, and confining beds of mudstones. Hydrogeological, hydrochemical and isotope hydrology studies show that most artesian springs and flowing water bores in the GAB derive their water from the main Jurassic–Lower Cretaceous Cadna-owie Formation – Hooray Sandstone aquifer and its equivalents. Focusing on springs in South Australia, this paper provides a summary of the hydrogeology of the GAB, including zones of recharge and regional groundwater flow directions, with a major focus on summarising understanding of the occurrence and formation of springs.

Keywords: artesian springs, Great Artesian Basin, hydrogeology, hydrochemistry, isotope hydrology, spring deposits

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Introduction

The Great Artesian Basin (GAB) is a confined groundwater basin, underlying about 1.7 million km^2, around one-fifth the area of Australia, within Queensland, New South Wales (NSW), South Australia (SA) and the Northern Territory (NT), where artesian springs are present in 13 major groups (supergroups in Figure 1; Habermehl, 1982, 2020). Most of the basin underlies arid and semi-arid regions with low rainfall, whereas the most northern parts of the GAB have high tropical seasonal rainfall.

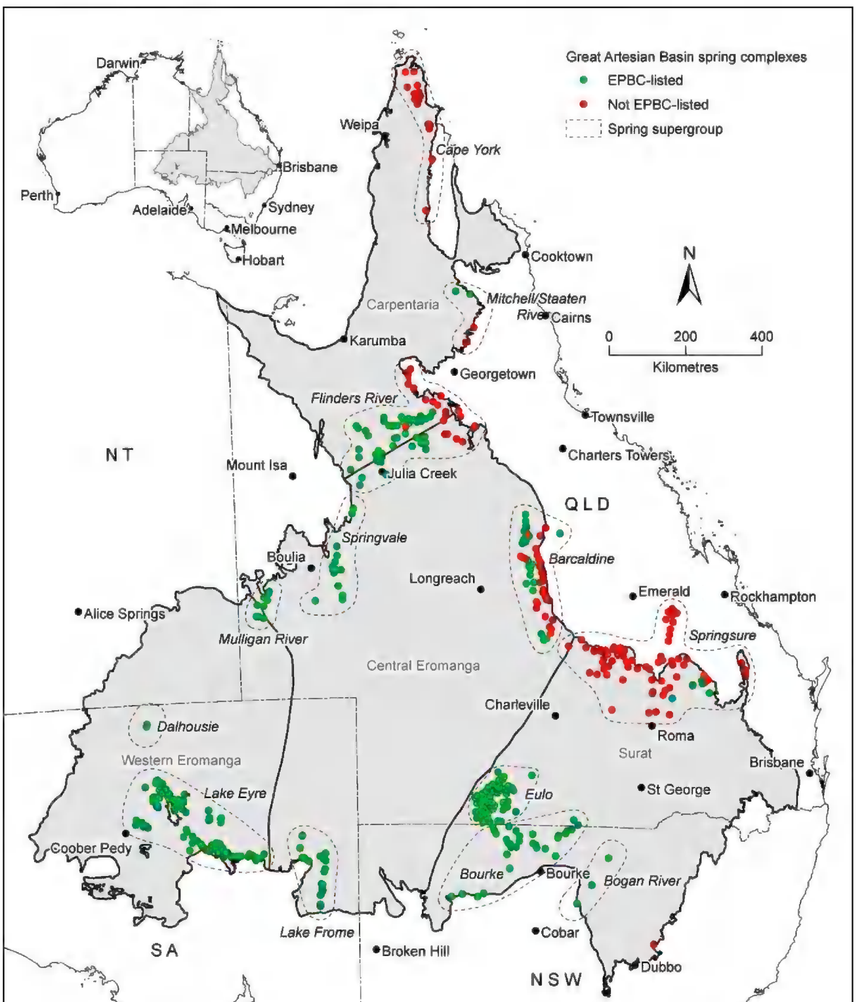
Artesian springs and areas of seepage are abundant in the marginal areas of the basin, especially in the southern and south-western discharge areas, and near the eastern recharge areas. The largest concentration of springs and their sedimentary deposits, mainly tufa carbonates but also mud, forming conical mounds and platforms, is present near the south-western margins (Habermehl, 1982, 2020; Keppel et al., 2011). Springs have probably developed over several climatic cycles, and dating of spring deposits shows age ranges up to 740,000 ± 120,000 years, with some springs most likely older (Habermehl, 2020; Prescott & Habermehl, 2008; Priestley et al., 2018).

Springs are of immense cultural and ecological importance, in particular to Aboriginal Peoples,

who have a strong connection with their land and the associated resources, especially spring watering points in desert areas (Badman, 2000; Hercus & Sutton, 1985; Moggridge, 2020; Silcock et al., 2020).

Many GAB springs, essentially natural surface discharge points of the basin's aquifers, have developed associated groundwater-dependent ecosystems, and support populations of unique and threatened fauna and flora (Fensham & Fairfax, 2003; Fensham et al., 2010, 2016; Gotch, 2006, 2013; Noble et al., 1998; Ponder, 1986; Rossini et al., 2018). The conservation significance of GAB groundwater-dependent ecosystems and their biological communities has been recognised, and they are protected under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act, 1999), as shown in Figure 1.

Figure 1. Great Artesian Basin showing the location of the main spring supergroups and complexes. Locations in green are listed and protected under the EPBC Act (1999), while those in red are not listed under this Act (Source: Smerdon et al., 2012a, with permission from CSIRO, Australia).



Following European settlement, springs became some of the earliest watering points for livestock and led to the discovery of the large-scale occurrence of artesian water in the GAB following construction of the first free-flowing artesian water bore in 1878 (Habermehl, 1980, 2020). Drilling of bores for stock, domestic and town water supplies expanded rapidly from the 1880s onwards (Brake, 2020; Habermehl, 1980, 2020).

Geological mapping of the intake beds in Queensland and NSW and along the eastern, northern, north-western and southern basin margins, combined with the information from drill holes, enabled the determination that the Jurassic–Lower Cretaceous sedimentary sequence contained significant artesian groundwater supplies, and assisted in the determination of the shape and size of the GAB (Pittman, 1914). By the end of the nineteenth century, many accepted the basin as a classic artesian groundwater basin.

A range of activities is very dependent on artesian groundwater from the basin provided by flowing artesian and pumped artesian (sub-artesian) water bores (Habermehl, 2020). Activities include sheep grazing (wool) and beef cattle farming, homestead and town water supplies in the rangelands since the 1880s, petroleum ventures since the 1960s, and mining activity within and outside the GAB area since the 1970s–1980s.

Diminishing flows and pressures in artesian bores and springs because of groundwater exploitation via numerous bores increasingly alarmed bore owners, and ultimately state governments became involved in efforts to reduce wastage of groundwater from many of the privately drilled bores. Once state governments passed legislation to control the use of sub-surface water in the early 1900s, bores had to be licensed, detailed information provided and bores completed according to prescribed standards (Brake, 2020; Cox & Barron, 1998; Habermehl, 2020; Reyenga et al., 1998).

Systematic investigations of the groundwater conditions in the GAB increased markedly as a result of the five conferences (ICAW – Interstate Conferences on Artesian Water), held in 1912, 1914, 1921, 1924 and 1928 (Habermehl, 1980, 2020). Although artesian springs were listed in the reports of these conferences, information on artesian springs was limited. The Commonwealth Bureau of Mineral Resources, Geology and Geophysics (BMR) carried out further studies of GAB artesian springs from the mid-1970s as part of its GAB hydrogeology study; these studies were continued subsequently by the BMR's replacement – the Australian Geological Survey Organisation (AGSO since 1992; Geoscience Australia since 2004). They concentrated initially on the distribution and hydrogeological characteristics of springs (Habermehl, 1982, 2020).

The purpose of this paper is to describe the hydrogeology and hydrochemistry of springs, including zones of recharge and regional groundwater flow directions, discharge characteristics, and the structure, lithological composition and depositional age of spring deposits. This hydrogeological foundation supports the papers that follow in this *Royal Society of Queensland* Special Issue on threatening processes, management options and conservation of GAB springs.

Hydrogeology

The GAB is a multi-layered, confined aquifer system, with artesian aquifers in Triassic, Jurassic and Cretaceous fluvial, fluvio-lacustrine and other continental and shallow marine quartzose sandstones (Habermehl, 1980, 2020). Intervening confining beds or aquitards consist of Jurassic siltstone and mudstone, and thick Cretaceous marine mudstone sediments form the main confining units (Figures 2 and 3; Habermehl, 1980, 2020; Habermehl & Lau, 1997; Radke et al., 2000; Ransley et al., 2015; Smerdon et al., 2012a,b).

The sedimentary sequence of the GAB is up to 3000 m thick and forms a large synclinal structure, uplifted and exposed along its eastern margin since the Late Cretaceous and Early Tertiary. This uplift of the Great Dividing Range, where most recharge takes place from rain falling on and infiltrating into exposed or sub-cropping sandstones, and from creeks and rivers, caused the elevation difference between the ranges and the low elevation of most of the basin area and its sub-surface sandstone aquifers. It also created the artesian conditions and locations where groundwater under pressure in an aquifer would rise above the ground surface if a water bore were constructed. The difference in these potentiometric elevations results in a predominantly south-westerly direction of groundwater flow from eastern recharge

areas to discharge areas. The artesian conditions of the aquifers result in natural flowing artesian springs and also the flow of artesian water from bores drilled into the aquifers (Figures 2 and 3).

Detailed descriptions of the geology, hydrogeology and aspects of the occurrence of artesian springs are given in Fensham & Fairfax (2003), Fensham et al. (2016), Flook (2020), GABWRA (2012), Green et al. (2013), Habermehl (1980, 1982, 2001a,b, 2020), National Water Commission (2013), Office of Groundwater Impact Assessment (OGIA) (2016) and Radke et al. (2000).

Figure 2. Map of Australia showing the location of the Great Artesian Basin, extent of GAB aquifers, and structure contours on the base of the Rolling Downs Group/top of the Cadna-owie Formation – Hooray Sandstone (main aquifer) and equivalents (after Habermehl, 2001a, 2020; with permission from the Geological Society of Australia).

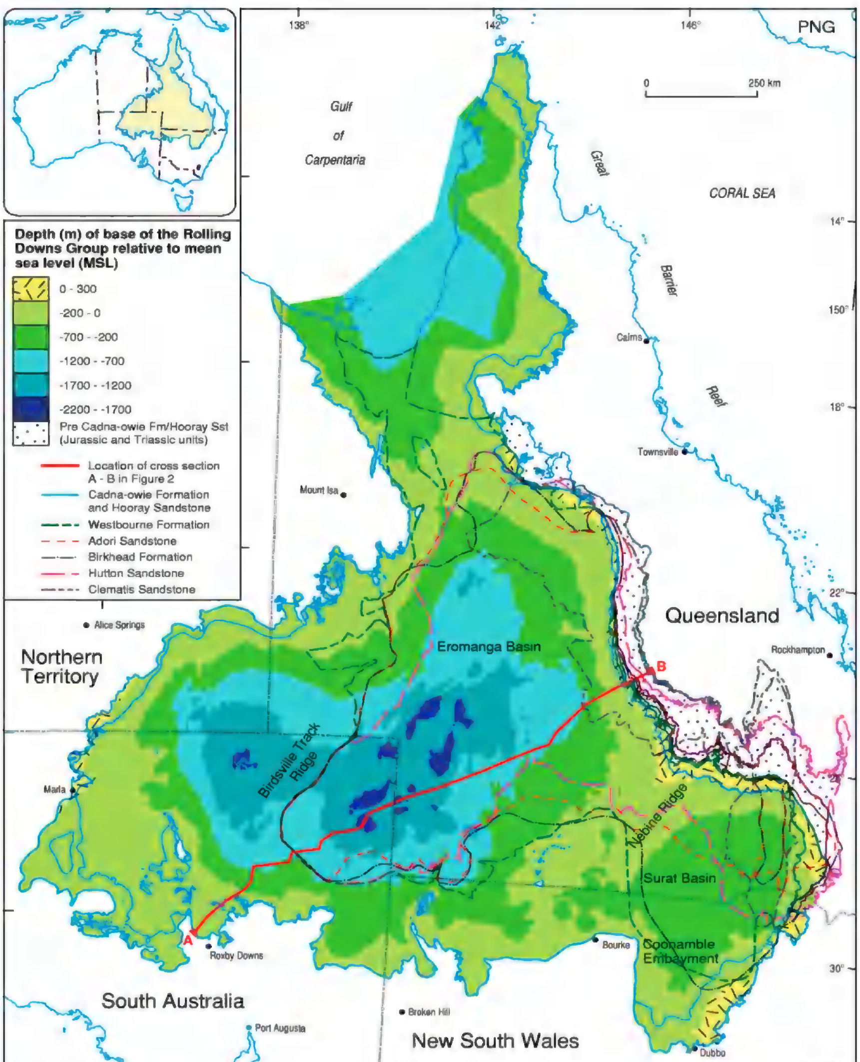


Figure 3. Geological cross-section of the Great Artesian Basin (see Figure 2 for location of the cross-section A–B, after Habermehl, 2001a, 2020; Habermehl and Lau, 1997; with permission from Geoscience Australia).

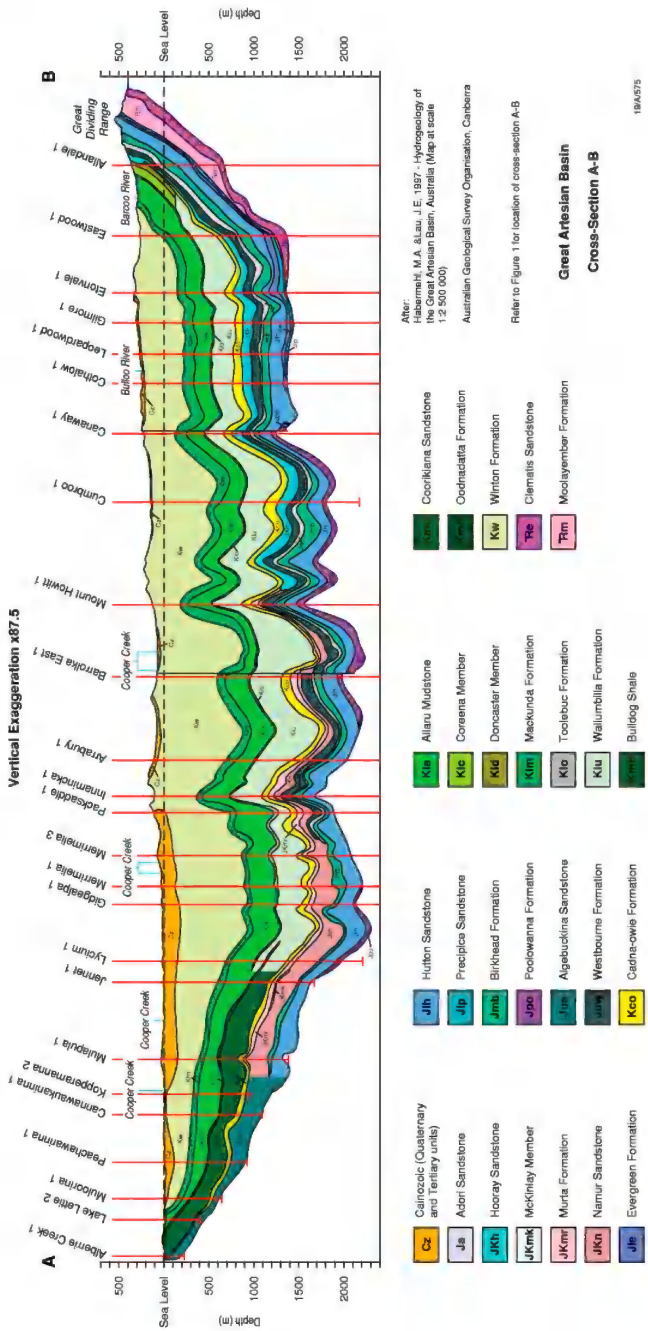
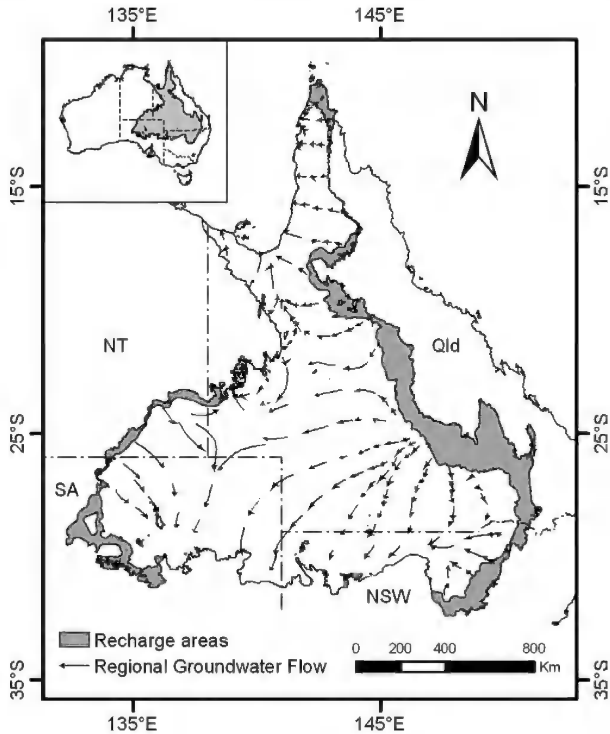


Figure 4. Directions of regional artesian groundwater flow in the Great Artesian Basin (after Habermehl, 1980, 1986, 2001; Prescott & Habermehl, 2008, with permission from Geological Society of Australia).



Recharge to the aquifers occurs predominantly in the eastern marginal areas and is derived from rainfall on the western slopes of the Great Dividing Range, where the main aquifers are exposed or subcrop (Habermehl et al., 2009; Kellett et al., 2003; McMahon et al., 2002), and from creeks and rivers. The area receives relatively high rainfall, whereas the western margin of the basin in the arid centre of the continent receives minor rainfall and thus little recharge (Keppel et al., 2013).

Regional groundwater movement in the aquifers is towards the southern, south-western, western and northern margins, where artesian springs provide natural discharges (Figures 1, 2 & 4; Habermehl, 2020; Habermehl & Lau, 1997; Keppel et al., 2013; Love et al., 2013; Smerdon et al., 2012a,b). Residence or travel times of artesian groundwater range from almost recent in the recharge areas to more than one million years near the centre of the GAB (Habermehl, 2020).

Hydrochemistry and Hydrogeology

BMR and its successors carried out hydrochemistry and isotope hydrology studies from 1974 to 2009. Their interpretation has provided significant information on the origin, recharge, movement, groundwater flow patterns and residence times of GAB groundwater. Waterbores and springs were sampled throughout the GAB by a number of Australian and overseas scientists and organisations (Habermehl, 2020). Deuterium and oxygen-18 stable isotope data from artesian groundwater in the GAB plot on or near the Global Meteoric Water Line and confirm the origin of artesian groundwater as meteoric (Airey et al., 1983; Bentley et al., 1986; Calf & Habermehl, 1984; Habermehl, 2020; Habermehl et al., 2009; Kellett et al., 2003; Radke et al., 2000). This was a contentious issue during the early twentieth century when connate or plutonic origins of the groundwater were suggested (Endersbee, 2005; Gregory, 1906).

The hydrochemistry of artesian groundwater and springs is closely associated with the hydrochemistry of the source of the groundwater, usually the Cadna-owie – Hooray aquifer (Habermehl, 1986, 2020; Herczeg et al., 1991; Radke et al., 2000). The groundwater derived from the eastern recharge areas within the main aquifers is characterised by Na-HCO_3-Cl type water, with usually 500 to 1500 mg/L total dissolved solids, and water from the western recharge areas characterised by Na-Cl-SO_4 (Habermehl, 1980, 1983, 2001a, 2020; Radke et al., 2000).

The hydrogeological characteristics of the main confining aquitard overlying the main confined aquifer, the Cadna-owie – Hooray aquifer, have been studied in detail (Hasegawa et al., 2016). The BRS (Bureau of Rural Sciences, where the GAB project and its staff were located from 1998 to 2009) and their Japanese scientific counterparts drilled two fully cored holes: (i) one down-gradient from the basin's recharge area near Richmond, Queensland in 2004, to a depth of 264 m; and (ii) near the discharge margin of the basin near Marree, SA in 2005, to a depth of 197 m (Habermehl, 2006a,b). Samples of ^{36}Cl and ^{37}Cl from rock cores were used to characterise the hydrodynamics of the main confining bed, the Rolling Downs group, and the main confined aquifer (Hasegawa et al., 2016). Results show that the groundwater flow in the confining mudstone layer is less than 10^{-5} m/year because diffusion is dominant. Spring flows will therefore mainly occur where the sedimentary sequence is disturbed and permeability and porosity increased, such as within or near geological faults.

A range of studies has been undertaken to assess flow velocity and residence time in GAB aquifers, including the analysis of cosmogenic ^{3}He, ^{4}He, ^{14}C and ^{36}Cl radioisotopes (Habermehl, 2001a, 2020). These studies indicate that artesian groundwater movement is in the order of 1 to 2.5 m/year. Groundwater ages, residence or travel times of the artesian groundwater from the eastern recharge areas to the central and south-western parts of the GAB are up to one to two million years.

Thermal Gradients

Geothermal gradients in the GAB vary widely, with a mean of about 39°C/km and a range of about 15°C/km to 100°C/km (Polak & Horsfall, 1979). Maps and data on groundwater temperatures in the basin and geothermal gradients are shown in Habermehl (2001b, 2002), Habermehl & Lau (1997) and Habermehl & Pestov (2002). The central and south-western areas of the GAB overlie a large area where estimated crustal temperatures between 180° and 300°C occur at depths of 5 km (Chopra & Holgate, 2005). Groundwater temperatures of flowing artesian bores tapping the Lower Cretaceous–Jurassic aquifers range from about 30° to 100°C (the latter at Birdsville), and artesian spring temperatures range from about 20° to 45°C, with springs at Dalhousie Springs (SA) having the highest temperatures, up to mid-40°C (Smith, 1989; Radke et al,, 2000; Wolaver et al., 2020). Many artesian springs have elevated water temperatures, in particular most of the springs in the south-western part of the GAB, an indication of the usually deep origin of the groundwater and aquifers, and/or high temperatures of rocks at depth.

Spring Nomenclature

Eleven groups of springs were initially identified (Habermehl, 1982) and later defined as supergroups by Ponder (1986). Subsequently, two more groups were recognised, and extensive datasets of individual spring locations were prepared by Fairfax & Fensham (2003) and Fensham & Fairfax (2003) in Queensland, by Gotch (2006, 2013) and Gotch & Defayari (2006) in SA, and by Pickard (1992) in NSW.

Ponder (1986) proposed the basic spring terminology, ranging from the different parts and vents of individual springs, to the association of springs in groups, to spring complexes, and ultimately to large groups of springs called supergroups (Figure 1). Abbreviated definitions of spring occurrences, ranging from individual vents to springs, spring groups, spring complexes and supergroups, are given in Table 1.

Most of the springs occur in groups, covering relatively small areas. This occurs because there is a relationship with geological faults, or where the artesian groundwater from the underlying aquifer breaks at that location through relatively thin overlying confining beds towards the ground surface, or near the abutment of confined aquifers bordering older, impermeable basement rocks (e.g. south-western margins) and near some basement highs between

sedimentary basins, e.g. near Eulo and areas north of Julia Creek (Figures 1, 2 & 3) (Whitehouse, 1954; Habermehl, 1980, 1982; Flook, 2020).

The majority of the artesian groundwater discharging from springs originates from the eastern recharge areas and is derived from the Cadna-owie – Hooray aquifer and its lithostratigraphic equivalents (Habermehl, 1980, 2001a,b, 2020). Springs also occur near recharge areas in the eastern margins, where many springs are the result of 'overflow' or 'rejection' of recharge into the aquifers, or result from the intersection of local topography and aquifer sandstones (e.g. valleys cutting into aquifers).

Groundwater from the western recharge areas feeds more than 80 flowing artesian springs in the Dalhousie Springs area in South Australia (Figure 5). Dalhousie Springs is set in the core of the Dalhousie anticline, which is uplifted to a dome, breached and eroded, with major geological faults located in the dome structure. Groundwater from the Cadna-owie Formation and Algebuckina Sandstone moves to the ground surface and produces these springs (Zeidler & Ponder, 1989; Smith, 1989; Wolaver et al., 2020). Krieg (1989) estimated the origin of the springs at not more than one to two million years ago. Dolomitic carbonate caps (deposited by springs) on mudstone hills exist in the eroded anticline core, and many springs produce small to very large (up to 160 L/s) flows of groundwater. Mud mounds are present in many areas at Dalhousie, where mud is pushed upwards, but little water appears on the surface. Dalhousie Springs produces the largest amount of GAB artesian spring groundwater in South Australia.

Spring Discharge and Deposits

Continuous measuring and automatic digital data collection equipment was constructed by the author and BMR/AGSO technical staff and maintained at four Dalhousie springs for about a decade from 1990 (Habermehl, 1990). Continuous records of meteorological data on rainfall, temperature, wind direction/strength and barometric pressure were recorded at the climate station. Discharges and continuous water levels were recorded at constructed measurement weirs at four selected springs. The locations of the measured springs and weirs 1, 2, 3 and 4 are shown in Figure 6.1 in Smith (1989), and in Appendix 1 and Figure 2 in Wolaver et al. (2020). These springs and other selected springs in the Dalhousie area were repeatedly sampled (usually at six-monthly intervals) by the author and BMR/AGSO technical staff for hydrochemistry and isotope analyses during the 1970s and 1980s (including during the 1985 Dalhousie Springs Expedition; Zeidler & Ponder, 1989), and on a regular basis during the 1990s, until 1997 (data listed in Radke et al., 2000). Weir 2, located in the outflow channel of the spring-fed main pool (Dalhousie 'swimming pool'), shows the discharge of the pool to be around 160 L/s, the largest flow from any of the Dalhousie springs.

The water levels (and thus discharges) of the artesian springs at Dalhousie appear to be influenced mainly by fluctuations in barometric pressure, whereas the flow in the outflow channels was influenced by the quantity and growth of the bordering vegetation (in particular the common reed – *Phragmites australis*). Temporary removal of this vegetation following fires caused by thunderstorms had an immediate effect, evidenced as increases in water levels and discharges.

Many of the springs in the south-western GAB deposit tufa and travertine carbonate sediments (Figure 6A). In the south-western parts of the basin, some springs have built up conical mounds several metres high, several metres or tens to hundreds of metres in diameter and several to tens of metres thick (Figure 6B). Others have built up large platform deposits; examples are shown in Prescott & Habermehl (2008) and in Figures 6A–D. Conical mounds consisting of mud, brought up as liquid mud by spring flows, occur in a number of locations in the GAB, in particular in the Eulo area, Queensland (Figure 6C) and at Dalhousie Springs, South Australia (Figure 6D).

Spring mounds can develop by a number of processes (Fensham et al., 2010; Habermehl, 1982), including:

- by upward transport of sub-soil or mud from the confining bed to the ground surface by artesian water flow from the aquifer or overlying aquitard;
- by the expansion of montmorillonite surface clays;
- by the accretion of calcium carbonate as cemented travertine;

- by the accumulation of mud, silt and sand produced by springs and aeolian sand; and
- through the development of peat from spring wetland vegetation.

Spring mound morphology is controlled by spring discharge rates, hydrochemistry, evaporation, the influence of organic and inorganic carbonate precipitation, and by erosion.

Lithological Composition

In 1985, the author and BMR technical staff drilled twenty-three fully cored drill holes into fossil carbonate spring mound deposits southwest of Lake Eyre to determine their thickness and lithology (Figure 7). The sediments generally consist of calcite and dolomite, occurring as tufa, travertine and very fine-grained or crystalline carbonate deposited as a chemical precipitate from the artesian groundwater, and precipitated by a combination of chemical, algal and bacterial action (Habermehl, 1986; Keppel et al., 2011; Keppel et al., 2012). Many of the spring deposits contain fossil reed casts and mollusc fossils. Thicknesses of the drilled carbonate mound deposits range from almost 5–30 m. Radke (1990) determined and described the sedimentary petrology of the drill cores from the 23 drill holes. The drill cores are stored at Geoscience Australia, Canberra, ACT.

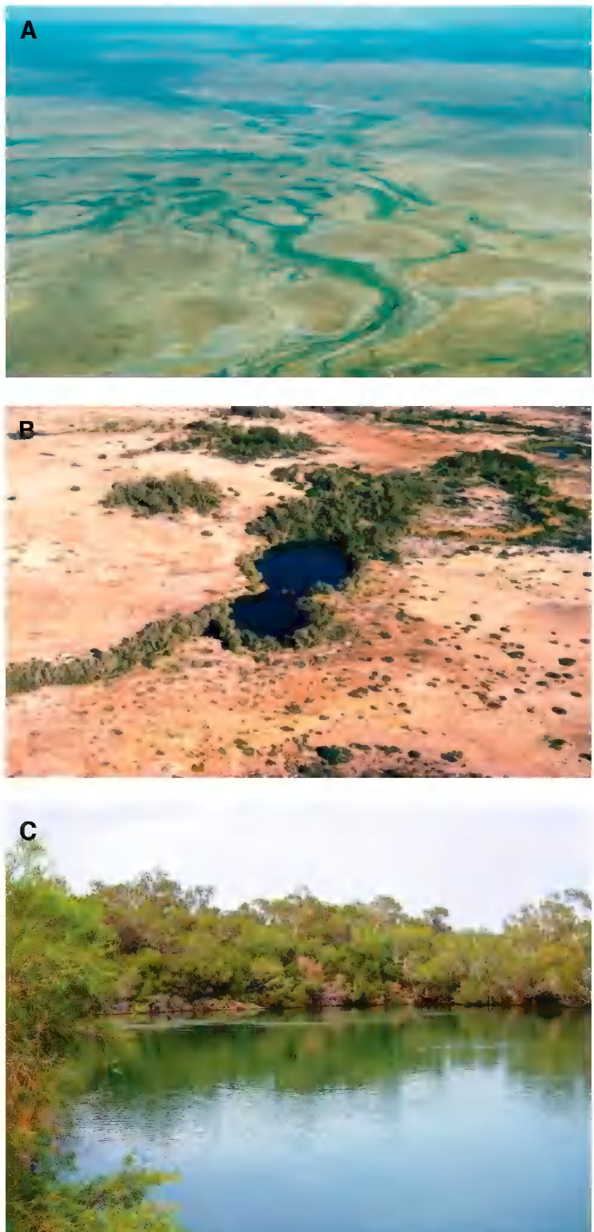
Thicknesses of the spring deposits were also determined through measurements of the geological profiles of several of the spring mounds, including Hamilton and Beresford Hills. Both mounds show the original spring outlets on top, which are now dry, and overlie the hard, lithified carbonate deposits (Habermehl, 1982; Prescott & Habermehl, 2008). These springs dried up in past geological times, when the potentiometric surface was lowered over time as nearby lower-level springs were breaking out at the ground surface, and the adjoining region was lowered by erosion of the (underlying) soft Cretaceous clayey sediments during more recent geological time (Habermehl, 1982). Caps of carbonate spring deposits protect the underlying pedestal of (Cretaceous) clayey sediments from erosion (Figure 8).

The Hamilton and Beresford springs and mounds (and many other springs and spring deposits) are located along a major NW–SE fault line, the Norwest Fault. Several springs and spring deposits between Strangways Springs and Horse Springs are aligned in the Torrens Hinge Zone (Krieg et al., 1991). Strangways Springs is another elevated feature, protected from erosion by its carbonate platform (elevated in the landscape) and covered by a number of active and inactive carbonate spring mounds, some of them probably aligned along fault(s) within the Strangways platform (Figure 6B). Elizabeth Springs (South Australia) shows a large carbonate mound, which is still active, with water escaping at several levels and creating small and large water-covered, stepped terraces (also at Blanche Cup Spring), where currently carbonate precipitation still takes place. Its mound is partially collapsed (inwards-dipping terraces) and broken up by faults, possibly because of the weight of the carbonate mound overlying saturated mudstone. Drill holes at Elizabeth Springs, at the base of the carbonate hill or mound, show the carbonate deposits to be up to 30 m thick and probably thicker, as the drill hole is located some distance away from the main mound.

Table 1. GAB spring nomenclature and definitions (Fensham & Fairfax, 2003).

Spring nomenclature	Definitions
Vent	Point of water discharge at the ground surface.
Spring	Vent or vents where the outflow forms a single spring wetland.
Spring group	Multiple springs, with no adjacent springs more than 1 km apart, and all springs in a similar geomorphic setting.
Spring complex	A group of springs or spring groups with no adjacent pair of springs or spring groups more than 6 km distant, and all springs in a similar geomorphic setting.
Supergroup	Major regional cluster of spring complexes (13 supergroups are depicted in Figure 1).

Figure 5. (A) Aerial photo of part of Dalhousie Springs (northern South Australia), looking south, showing vegetation-lined creeks (spring tails) with artesian groundwater flowing from springs within an arid landscape (Source: M. A. Habermehl); (B) Low-level aerial view of the main pool at Dalhousie Springs (Source: FOMS, https://www.friendsofmoundsprings.org.au/featured-mound/dalhousie-springs/); (C) Main spring-fed pool at Dalhousie Springs (Dalhousie 'swimming pool') (Source: M. A. Habermehl).



Depositional Age

Ages of spring deposits sampled in 1993 in this area (Figure 7) have been determined by thermoluminescence, with Elizabeth Springs (South Australia) showing an age of at least 740,000 years ± 120,000 years (Prescott & Habermehl, 2008). Subsequent uranium series show ages of 466,000 ± 135,000 years for Beresford Hill, and 465,000 ± 43,000 years for Dalhousie Springs (Priestley et al., 2018). Palaeomagnetic studies at Beresford Hill suggest ±700,000 years for carbonate spring deposits overlying the hill (unpublished data, M. Idnurm and M. A. Habermehl, 1985). The range of episodic ages of the sedimentation of travertine spring deposits in several locations in the Lake Eyre region is consistent with wet (geological) periods in central and southern Australia and could indicate times of higher regional rainfall in the recharge areas of the basin (Magee et al., 2004; Prescott & Habermehl, 2008; Priestley et al., 2018). However, Ring et al. (2016) and Uysal et al. (2019) propose an alternative explanation for the paleohydrogeology and paleoclimate interpretation of Priestley et al. (2018). They consider that CO_2 degassing from the earth mantle associated with active faulting played a major role in the spring travertine (carbonate) precipitation in the area south-west of Lake Eyre. Most springs in this area are aligned with or parallel to the major Norwest Fault and Torrens Hinge Zone (Drexel & Preiss, 1995; Krieg et al., 1991, 1992).

Figure 6. (A) Travertine carbonate deposits forming spring terraces between Elizabeth Springs and Kewson Hill, south-west of Lake Eyre, South Australia (geological hammer for scale); (B) Active flowing spring mound consisting of spring-deposited carbonate at Strangways Springs (south-west of Lake Eyre, South Australia), approximately 6 m in height (person left of centre for scale); (C) Spring mound composed of mud in the Eulo area, Queensland; (D) Mud spring at Dalhousie Springs, South Australia (Source: All photographs by M. A. Habermehl).

Figure 7. Locations of fully cored drill holes in spring deposits south-west of Lake Eyre, South Australia (upper plot, after Prescott & Habermehl, 2008, with permission from Geological Society of Australia); finer details of the locations of the fully cored drill holes in spring deposits at Elizabeth Springs (middle plot) and Hamilton Hill (lower plot).

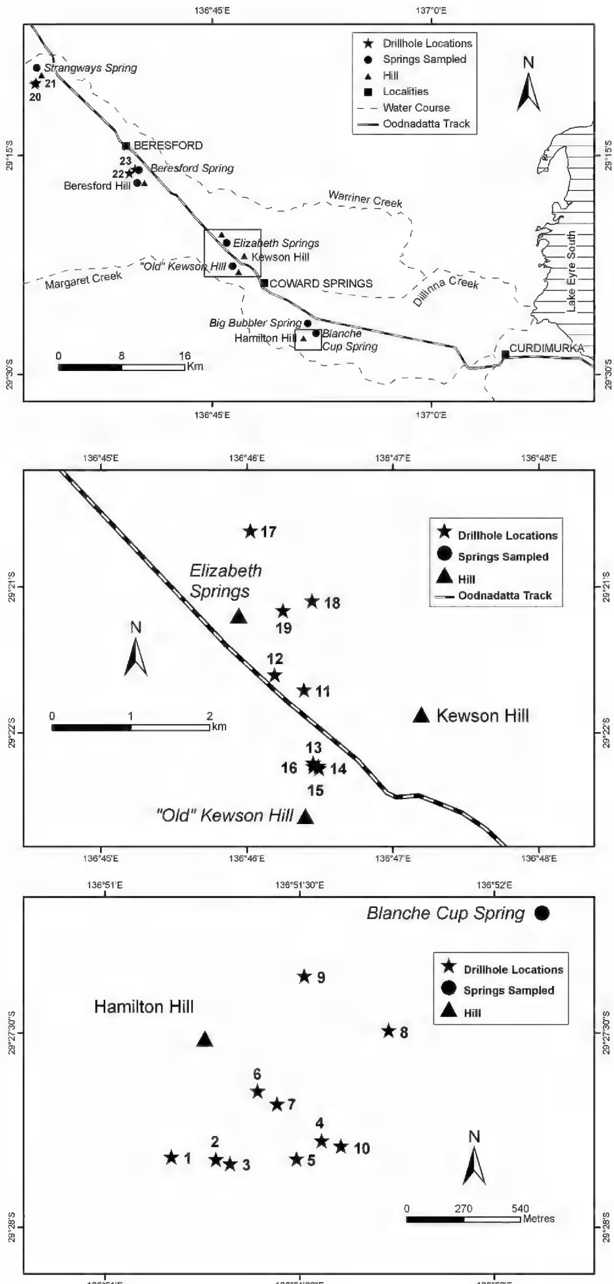


Figure 8. Hamilton Hill (in the background), similar to Beresford Hill, with a non-active (dry) fossil spring and spring-deposited carbonate cap overlying a pedestal of Cretaceous mudstone. Big Bubbler Spring (south-west of Lake Eyre, South Australia) in the foreground shows upwelling artesian groundwater, silt and sand (Source: M. A. Habermehl).

Conclusions

Springs of the Great Artesian Basin are natural surface discharge points of the basin's extensive aquifers, clustered into 13 supergroups and hundreds of complexes. Many springs have developed groundwater-dependent ecosystems supporting endemic flora and fauna, now protected by Australian's main environmental legislation, the EPBC Act (1999). This paper has provided an introductory hydrogeological foundation on groundwater flow patterns and ages, discharge from artesian springs and spring deposits. This foundation informs the papers that follow on processes that threaten the hydrology, physical habitat structure and persistence of springs and their endemic biological assemblages. It covers the history of extensive hydrogeological investigations and illustrates the remarkable variety of spring formations, such as the conical mound springs and travertine terraces in the south-western parts of the basin. Investigations reviewed herein highlight the importance of understanding the relationships between springs and their source aquifers, and the hydrogeological processes that create and maintain springs in the arid environments of the Great Artesian Basin.

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Evolution of Knowledge on Springs in the Surat and Southern Bowen Basins: Survey, Conceptualisation and Wetland Dynamics

Steven C. Flook[1], Jon Fawcett[2], Dean Erasmus[1], Dhananjay Singh[1], and Sanjeev Pandey[1]

Abstract

Permanent wetlands supported by discharge from the Great Artesian Basin (GAB) are of global significance due to their unique ecological assemblages and cultural values. Since 2005, rapid growth in coal seam gas (CSG)[a] development has occurred in the Surat Basin, a sub-basin of the GAB. In parallel with this expansion, there has been substantial investment by government and industry to identify spring wetlands and their source aquifers, understand natural variability in groundwater discharge and to manage predicted impacts resulting from groundwater drawdown. The assessment of consequences to the springs from groundwater drawdown relies upon sound hydrogeological conceptualisation including: the mechanisms through which springs occur; understanding of the wetland water balance; knowledge of historical spatio-temporal changes in wetland extent; and an ability to distinguish between the effects of groundwater drawdown from natural variability in the wetland water balance and other non-hydrogeological influences. In parallel with changes to groundwater pressure, key factors that influence wetland dynamics include the soils surrounding the wetlands, landscape setting, the type of groundwater flow system (local and/or regional), adjacent land use and climate. Integrating multiple lines of evidence and knowledge is pivotal to understanding the influences of a change in groundwater pressure on the abundance and resilience of biota that are dependent on the groundwater discharge. This paper provides a synthesis of the research and monitoring undertaken in the Surat and southern Bowen basins since 2011. Detailed surveys and hydrogeological conceptualisation have led to new insights on the occurrence and distribution of springs and the key influences on the spring wetland water balance. This knowledge has provided the scientific basis for the management and monitoring of predicted impacts. The approach of evolving the underpinning science to inform a specific management and monitoring requirement is more broadly applicable to groundwater-dependent ecosystems.

[a] Also referred to as coal bed methane.

Keywords: groundwater-dependent ecosystems, Great Artesian Basin, Surat Basin, spring dynamics, wetland water balance, coal seam gas

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Introduction

Wetlands associated with springs sourced from the Great Artesian Basin (GAB) are of international conservation significance. The GAB is a hydrogeological grouping of geological formations, comprising a number of component sub-basins (Habermehl, 2020). Collectively, this resource covers an area of 1.7 million km^2, nearly one-fifth of the Australian continent, across four states (Ransley & Smerdon, 2012). The Queensland portion of the GAB covers 65% of the state, and ranges in thickness from less than 100 m to more than 3000 m in the Eromanga Basin in Central Queensland (UWIR, 2019).

The Surat Basin, a sub-basin of the GAB (Figure 1), is a predominantly Jurassic and Early Cretaceous sedimentary sequence (deposited 60 to 200 million years ago) attaining a maximum thickness of around 2500 m (Habermehl, 1980; Hoffmann et al., 2009). The basin is a highly heterogeneous mix of alternating layers of sandstones, siltstones, mudstones and coal (OGIA, 2019). The primary CSG reservoir in the Surat Basin is the Walloon Coal Measures. Portions of the Surat Basin are underlain by the Bowen Basin.

Groundwater naturally discharges in the form of springs and baseflow to streams, predominately around the margins of the GAB. However, due to structural features such as faults or basement highs that occur between sub-basins, springs can also form away from the margins. Although many springs share similar hydrogeological mechanisms, there is significant diversity in their expression at the surface, driven largely by variability in the hydrochemistry, soils and local climatic conditions. Examples of springs across the GAB, which highlight the variability in their surface expression, are shown in Figure 2.

Figure 1. The GAB with sub-basins, major regional clusters of springs (spring supergroups, shown in blue) (Fensham & Fairfax, 2003), local (hatch) and regional recharge areas (dark grey around the GAB periphery), regional flow directions (orange arrows) (Ransley et al., 2015) and the Surat Cumulative Management Area (OGIA, 2019).

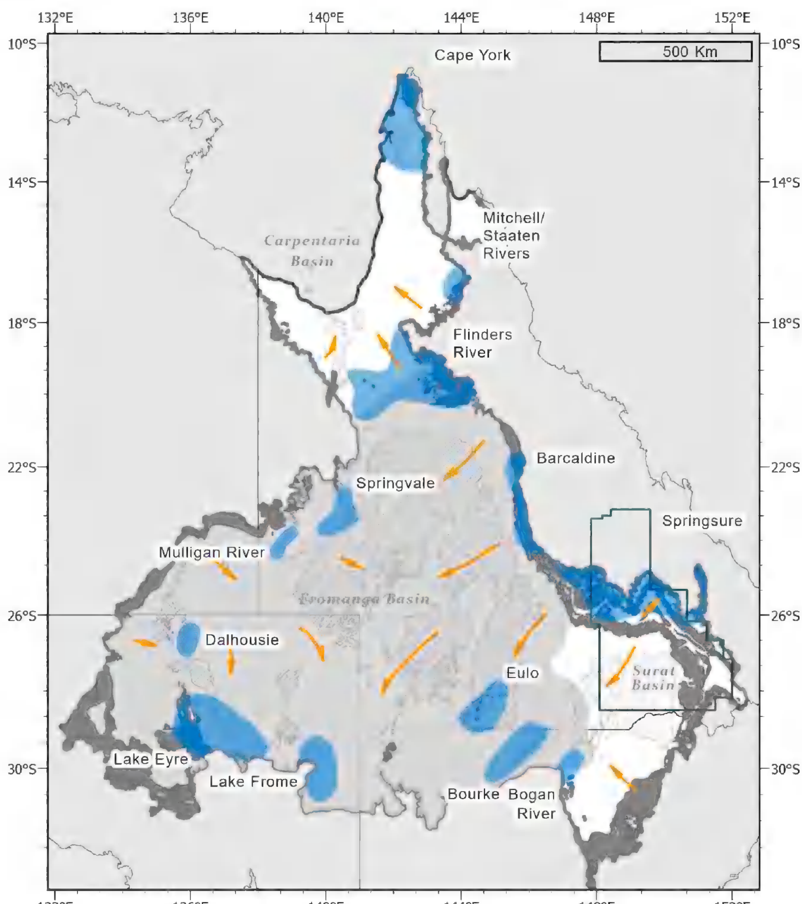


Figure 2. Examples of spring wetlands that occur in the Queensland portion of the GAB: (A) Springsure supergroup – 100 km N of Roma. (B) Springsure supergroup – 60 km WSW of Taroom. (C) Eulo supergroup – 200 km SW of Charleville. (D) Springsure supergroup – 100 km NNE of Roma. (E) Springvale supergroup – 300 km SE of Mt Isa. (F) Barcaldine supergroup – 140 km NE of Longreach.

A wetland associated with a spring can be subdivided into two distinct zones: the 'aquatic wetland extent' and the 'wetland extent'. The aquatic wetland extent represents the zone of permanent saturation and is dominated by aquatic species, as defined by Fensham & Fairfax (2009). The broader 'wetland extent' is a larger area of historical or periodic wetland extent. In this area, there may be

no aquatic species or free water, but key wetland indicators – wetland soil development – suggest historically significant periods of inundation.

There is a range of hydrogeological and non-hydrogeological stressors which have the potential to impact both the condition and wetland habitat. Change in groundwater pressure in aquifers that support springs is recognised as the most significant threat to spring wetlands (Fensham et al., 2010). Changes in groundwater pressure may occur in response to climatic variability and resultant recharge, consumptive water use and petroleum, and gas and mineral resource development.

In contrast to consumptive water use, groundwater extraction for CSG development is a more concentrated stressor on the groundwater system. In the Surat Cumulative Management Area (CMA) (160,000 km^2), CSG extraction commenced around 2005, within the Surat and southern Bowen basins. The rapid expansion of this industry was a key driver for the need to advance the understanding of springs in this area. In parallel, new knowledge on springs has been incorporated into the management and monitoring arrangements for all water users under the Water Plan (Great Artesian Basin and Other Regional Aquifers) 2017 (GABORA Water Plan).

In the Surat CMA, the primary CSG reservoirs are the Walloon Coal Measures (Surat Basin) and the Bandanna Formation (Bowen Basin). During the initial CSG development phase, the target reservoir must be depressurised, as the gas is adsorbed to the coal seams, held in place under hydrostatic pressure. This differs significantly from conventional petroleum and gas development, where oil and gas reserves are held within structural or stratigraphic geological traps, rather than under hydrostatic pressure. As a result, CSG wells initially produce significant amounts of water (termed 'associated water') and minimal gas. Over time, as the well develops and hydrostatic pressure in the reservoir reduces, discharge from the well is progressively dominated by gas (OGIA, 2019). Currently, the annual volume of associated water produced from the Surat Basin is about 50,000 ML (OGIA, 2019) from around 7000 production wells.

This extraction is in addition to a current consumptive and industrial water use across the CMA that exceeds 160,000 ML/year (OGIA, 2019) across shallow alluvial, basalt and GAB aquifers. The allocation and protection of consumptive water use is managed under the GABORA Water Plan, for purposes including stock and domestic, town water supply, agriculture and intensive livestock purposes.

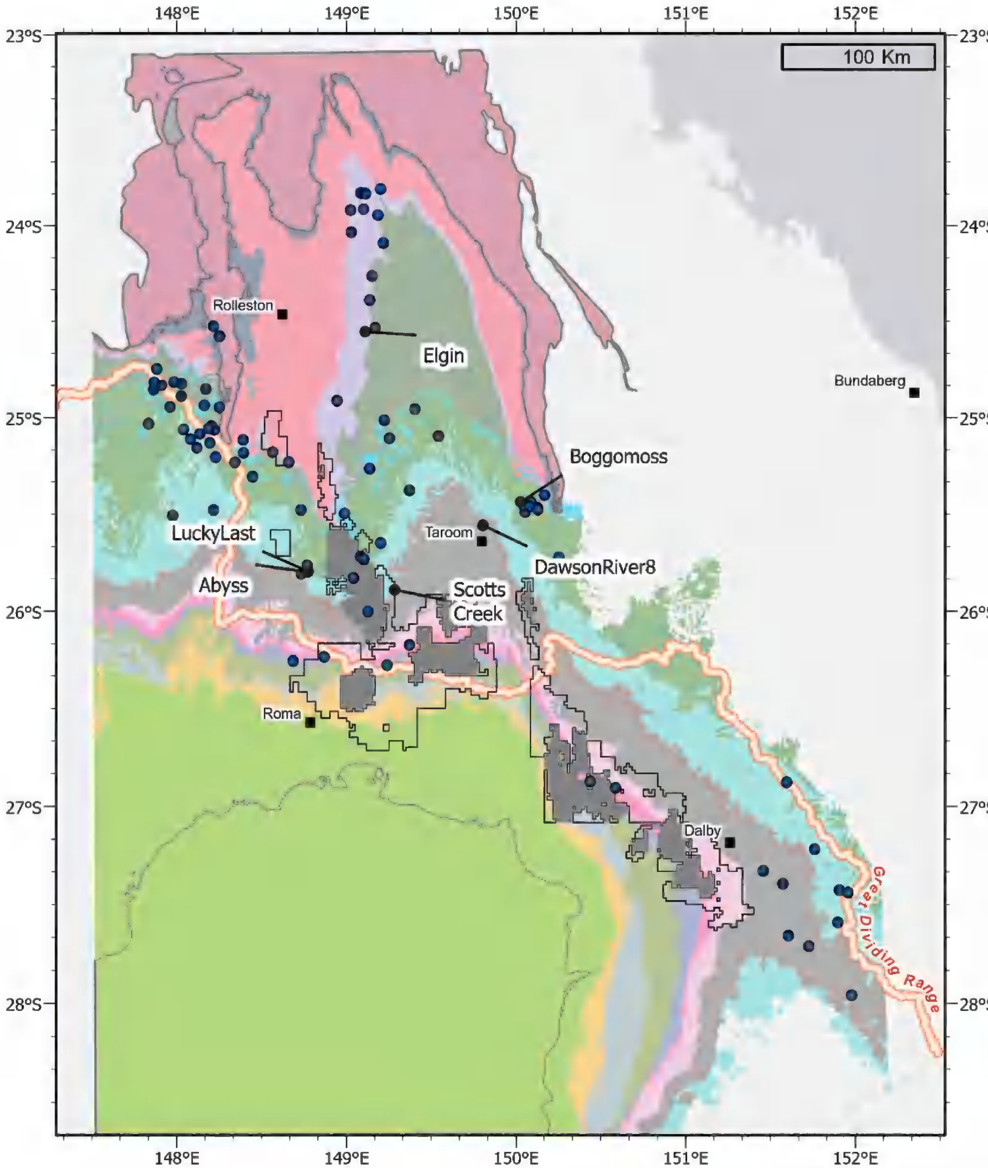
In response to the rapidly expanding CSG industry, there has been significant investment by the Queensland Government and industry since 2011 to identify and monitor springs in areas potentially affected by these activities. Within the Surat CMA, there are 88 spring complexes, of which 19 have high conservation values protected under Commonwealth (*Environment Protection and Biodiversity Conservation Act 1999* (the EPBC Act)) and state legislation.

Springs in this area are predominantly fed from the major aquifers including the Clematis Sandstone, the Precipice Sandstone, the Boxvale Sandstone Member of the Evergreen Formation, the Hutton Sandstone, the Gubberamunda Sandstone and the Bungil Formation (Figure 3). In addition to these aquifers, there are springs associated with the Tertiary volcanics and Cenozoic sediments.

Recent groundwater modelling (UWIR, 2019) predicts that several spring complexes are likely to be affected by groundwater drawdown as a result of CSG development. The accurate assessment of impacts and the development of appropriate mitigation and management strategies must be informed by knowledge of the ecological and cultural values of these sites, knowledge of factors that influence wetland extent and groundwater pressure in supporting aquifers, and knowledge of the historical variability in these systems.

For some spring wetlands, rainfall variability can be a significant influence on the wetland vegetation extent and condition. This results in a dynamic pattern of expansion and contraction in wetland extent in response to periods of higher rainfall and recharge to the source aquifer that feeds the wetland. In combination with changes in groundwater extraction, land use, disturbance by feral animals (such as pigs), exotic weeds, and grazing pressure during higher and lower rainfall periods, the temporal dynamics of the wetland extent – and habitat – can vary significantly.

Figure 3. Hydrogeology of the Surat and southern Bowen basins (surficial sediments removed) with selected spring complexes, showing existing (grey) and planned (hollow) CSG development (OGIA, 2019). Major aquifers include the Precipice (blue), Hutton (teal), Clematis (light purple) and Gubberamunda (dark purple) sandstones.



To assess change in wetland extent, a field-based methodology for the measurement of aquatic wetland extent has been established (Fensham & Fairfax, 2009). The method involves defining the edge of the wetland area by delineating the wetland boundary – where aquatic vegetation is less than 50% vegetation coverage.

In parallel with in-field mapping of the wetland

extent, remote sensing has been applied at the broad or regional scale (Ndayisaba et al., 2017; Nhamo et al., 2017; Petus et al., 2013; White & Lewis, 2011; Xie et al., 2016). Improvements in spatial resolution have enabled increased precision in wetland delineation (Davidson et al., 2018). However, remotely sensed imagery is only available for recent decades.

Given the high spatio-temporal variability in rainfall in Australia, analysis of a longer period of historical data is desirable. Prior to the inception of satellite-based imagery, opportunistically collected aerial photography – such as that collected for early mineral exploration – represents a unique source of historical data for comparative studies of wetland location and extent. In areas of high potential groundwater extraction, accurate location and elevation information, as well as knowledge of source aquifers and environmental values of springs, are necessary for a comprehensive assessment of potential impacts.

This paper provides an overview of some of the findings from field surveys, monitoring and research at groundwater-fed wetlands in the Surat CMA. The paper presents the evolution of knowledge in relation to springs, from field surveys through to remote sensing, to inform the conceptualisation of wetland dynamics. The components of the wetland water balance and both groundwater and non-groundwater influences on observed change in wetland extent over time are discussed. Understanding the drivers of spring dynamics is critical for determining appropriate monitoring methods and for understanding how changes in groundwater pressure could affect wetland ecosystems. Importantly, the approach is more widely applicable, as many of the methods and research questions are relevant to other parts of the GAB.

Management of Groundwater Impacts on Springs

In Queensland, the *Water Act 2000* (Water Act), the GABORA Water Plan and management protocol create the framework for the management of water use impacts on springs. The protection of flow to the identified groundwater-dependent ecosystems (GDEs) – including springs – is achieved through the water licence assessment process. Through this mechanism, cumulative predicted drawdown limits are recorded for each individual spring. These are assessed and managed during water licence transactions.

CSG development in Queensland is regulated by state and Commonwealth governments, which assess the potential for impacts on groundwater resources, associated ecosystems and other water users. In Queensland, the *Petroleum and Gas (Production and Safety) Act 2004* and the *Petroleum Act 1923* authorise petroleum tenure holders to undertake activities related to petroleum exploration and production. Prior to a tenure being issued, under the *Environmental Protection Act 1994* an environmental authority must be obtained, which primarily deals with the management of surface water and contamination as it relates to surface water and groundwater.

Petroleum tenure holders have a statutory right to take or interfere with groundwater. However, since 2010, under the Water Act, tenure holders are subject to a number of responsibilities to manage impacts on groundwater pressure arising from the exercise of underground water rights, including groundwater monitoring, the make-good of affected water supply bores and the mitigation of impacts on springs.

In areas of concentrated CSG development, the impacts on groundwater pressure resulting from individual tenure holders may overlap. In areas where this occurs, the Water Act allows for a CMA to be prescribed by the state, which allows for a cumulative approach to the assessment and management of these groundwater impacts (OGIA, 2019). The Surat CMA (Figures 1 and 3) was established in 2011 in response to expanding CSG development in the Surat and southern Bowen basins.

In the Surat CMA, the Office of Groundwater Impact Assessment (OGIA) is responsible for assessing cumulative groundwater impacts from resource activities and for developing appropriate water monitoring and spring management strategies. The assessment includes primary research and field investigations, system conceptualisation, regional groundwater flow modelling and development of integrated management arrangements. OGIA assigns responsibility to individual tenure holders for implementing specific management actions. The collective assessments and management arrangements are established in an Underground Water

Impact Report (UWIR), which is required every three years.

In parallel with the state approvals process, the Commonwealth Government also regulates new CSG activities through the EPBC Act, under which, nationally and internationally important flora, fauna, ecological communities and heritage places are recognised as "matters of national environmental significance" (MNES). As MNES relate to groundwater in the GAB, the community of native species dependent on natural discharge of groundwater from the GAB is listed as "Endangered" (Pointon & Rossini, 2020). Specifically, this is the ecological community associated with discharge springs, where groundwater emanates from a confined aquifer, not present at the surface.

In addition to individual species and communities, water resources are also recognised as MNES ("Water Trigger" EPBC Act amendment, 2013). The Commonwealth Government is therefore responsible for approving CSG projects, but that intervention is limited to consideration of impacts on water resources and other matters of national significance.

Monitoring and Research

Since the establishment of the Surat CMA in 2011, there has been significant investment in research to improve knowledge about the location, values and seasonal dynamics of springs. Prior to 2011, earlier spring surveys by the Queensland Government were primarily focused on recording springs' location and botanical information. Building upon that dataset, an extensive hydrogeological and botanical survey was led by OGIA (then the Queensland Water Commission) in 2011. The updated dataset provided the basis for the initial source aquifer assessments and was also used to characterise ecological values as part of the first Underground Water Impact Report for the Surat CMA (UWIR, 2012) (Queensland Water Commission, 2012).

Five spring complexes were predicted to be impacted by more than 0.2 metres in the long term. As a result, detailed desktop and field investigations were undertaken at these locations, in parallel with seasonal monitoring completed by industry in accordance with the UWIR 2012 and tenure holders' EPBC approval conditions across 17 spring complexes.

Under the EPBC Act, the Commonwealth Government set monitoring and other requirements on tenure holders as conditions of approval of CSG developments. The primary objective of monitoring at springs was to establish both an understanding of the natural variability and a baseline so that the potential impacts on the spring wetlands resulting from CSG water extraction may be identified.

Hydrogeological Conceptualisation

The overall approach to building knowledge about springs broadly applied the principles of the groundwater-dependent ecosystem toolbox (Richardson et al., 2011) – identify, characterise and assess the likely response to a change in the groundwater regime.

The hydrogeological, landscape and flora data collected between 2013 and 2015 were integrated to produce detailed ecohydrogeological conceptualisations (Flook et al., 2020) at a landscape and local scale level for 17 spring complexes.

Importantly, at each site, non-hydrogeological indicators of changes in the water balance – referred to as 'ecological endpoints' – were also identified. Ecological endpoints (Gross, 2003) represent key physical, biological and chemical elements of the spring wetland that are primarily influenced by groundwater discharge, and include indicators such as the extent of wetland vegetation that is dependent on groundwater discharge.

A detailed conceptualisation aids in the synthesis of an improved understanding of a spring's source aquifer and the mechanisms by which springs occur. These two hydrogeological elements underpin predictions of the likelihood of impact from a change in the groundwater regime, resulting in a change in groundwater discharge from the spring at the surface. The identification of ecological endpoints provides a useful tool for the assessment and monitoring of change in the wetland linked to groundwater. These components collectively form the basis of the impact assessment and monitoring of change.

Discharge Mechanisms

The occurrence and distribution of springs in the Surat CMA are primarily driven by regional and local geology and topography. They are also influenced by geological and hydrogeological features such as

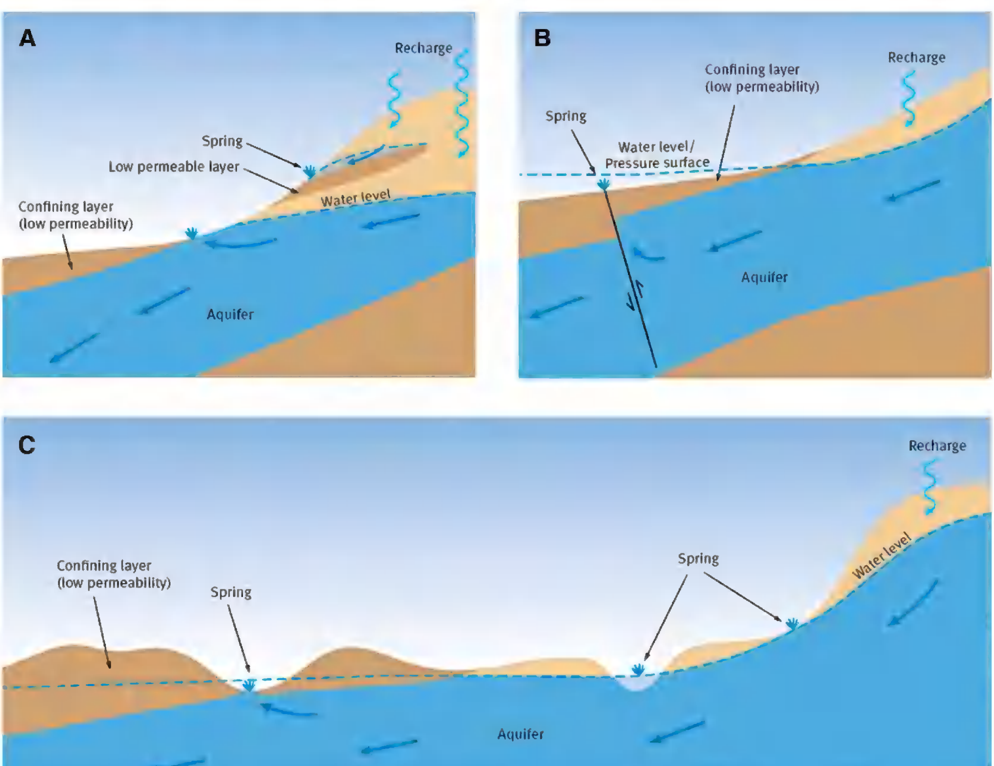
faults, changes in aquifer geometry and groundwater divides. Understanding the primary mechanism of connectivity to underlying aquifers is important for determining which aquifer is feeding the spring and critically informs the assessment of likelihood of a groundwater impact to a spring.

Building upon the work of Whitehouse (1954), Habermehl (1980) and Fensham & Fairfax (2003), three generalised hydrogeological mechanisms for spring formation are identified, noting that individual springs can occur due to more than one of these mechanisms (Figure 4):

(a) A spring can form where there is a change in the hydraulic properties of the geology within the landscape. Such a spring is often referred to as a contact spring. Where a higher-permeability layer overlies a lower-permeability layer, flow across the boundary is restricted. As a result, water tends to flow laterally and may reach the surface as a spring. This can occur where there is a change in permeability within a single aquifer or where there is a change in geology. Approximately 40 km north of Roma, two spring complexes have formed in this way – Six Mile and Spring Ridge.

(b) A geologic structure, such as a fault, can provide a path to the surface for water flow. If an underlying aquifer is confined by impermeable material and the water pressure in the aquifer is high enough, water can flow to the surface as a spring. Regional faulting features, such as the Hutton-Wallumbilla Fault and the Leichhardt-Burunga Fault, are associated with springs in the central area of the Surat CMA (OGIA, 2016).

Figure 4. Schematics showing the generalised mechanisms by which springs occur in the Surat Basin (after OGIA, 2019): (A) Change in permeability. (B) Presence of a geological structure. (C) Erosion of the surface geology.



(c) Erosion and dissection of the landscape by surface water flows can provide opportunities for groundwater to reach the surface. This can occur where an outcropping aquifer has been eroded to create a depression of sufficient depth to reach the watertable. This situation is generally associated with creeks and streams. In other areas, a confining unit may be dissected, resulting in a reduction in the thickness of the confining unit and providing an opportunity for groundwater to flow to the surface. Springs in the Surat CMA formed by erosion of the surface geology include springs in watercourses, such as the Dawson River.

These are generalised mechanisms by which springs occur. However, at many spring locations, a combination of mechanisms may exist and influence one another. For example, where structural features exist in the near surface (Figure 4B), these areas are more erodible and therefore erosion and dissection of the landscape may occur (Figure 4C) in parallel.

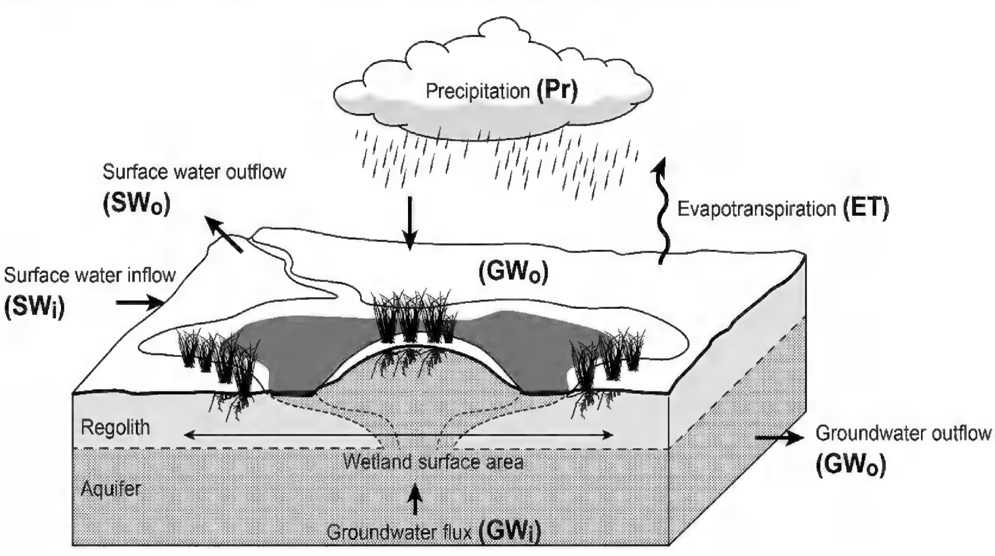
The discharge mechanisms can be further informed by analysis of hydrochemical data that have shown many wetlands receive groundwater inflows from both regional and local groundwater systems. Some springs (for example, at the Abyss complex) are fed by seasonal groundwater inflows in addition to regional groundwater discharge (Flook et al., 2020). The incorporation of multiple lines of evidence and the evolution of monitoring techniques aid in the refinement of a detailed subsurface hydrogeological conceptualisation, but also further refine the wetland water balance.

Wetland Water Balance

The detailed wetland conceptualisation highlights the importance of understanding the components of a spring's water balance. Under natural conditions, a spring's ecological composition and function intrinsically rely upon maintenance of the spring water balance. The water balance (Figure 5) includes all major inflows and losses from a spring.

Characterising the natural hydrological dynamics of the wetland system is critical to determining ecological water requirements of the dependent ecosystems and hypothesising potential consequences of a change to a component of the water balance.

Figure 5. Conceptual schematic of a spring wetland water balance (after OGIA, 2016).



$(Pr + GW_i + SW_i) - (ET + SW_o + GW_o) = \Delta S$ (saturated and unsaturated)

Variation in groundwater discharge and aquatic wetland extent has been observed through physical monitoring and mapping by industry and OGIA (OGIA, 2015b). Long-term variation is observed through the analysis of historical imagery and the presence of landscape features that indicate wetting or drying phases of the wetland area, such as dead trees, salt-scalded soil, collapsed spring vents, and spring vents that have stopped flowing.

Figures 6 and 7 show wetland area data for two spring vents at the Lucky Last spring complex, illustrating seasonal and long-term variability in the wetland supported by these springs. The extent of wetland vegetation and variability was assessed for the period 1948–2013 from opportunistically captured aerial photographs (OGIA, 2014).

At this location, there is significant variability in the aquatic vegetation extent through time. However, individual wetlands show a generally consistent trend of expansion and contraction across the historical period of record.

Similar to the analysis of a water level hydrograph, the measurement of aquatic wetland extent through time provides a monitoring signal and trend for subsequent analysis. The data represent the culmination of both the wetland water balance and non-hydrogeological influences on the wetland. Determining the influence of a change in groundwater pressure on the wetland requires detailed hydrogeological conceptualisation of the site and characterisation of the current and historical influences on the wetland.

Figure 6. Field-based mapping of the aquatic vegetation extent at the Lucky Last spring complex.

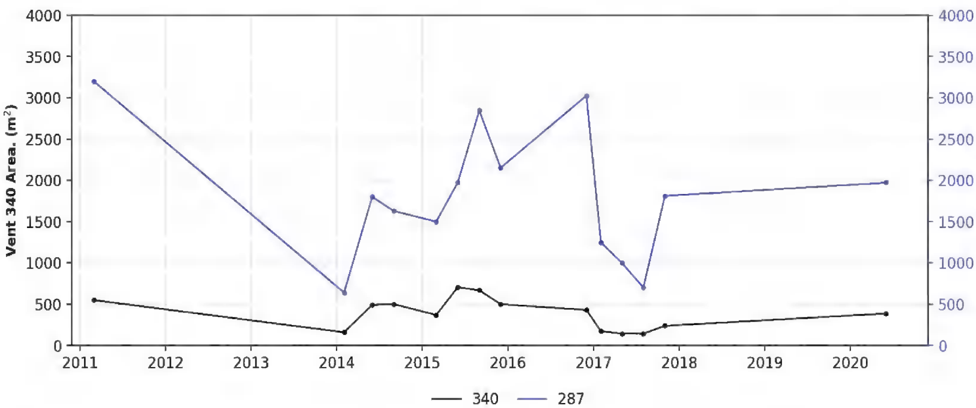
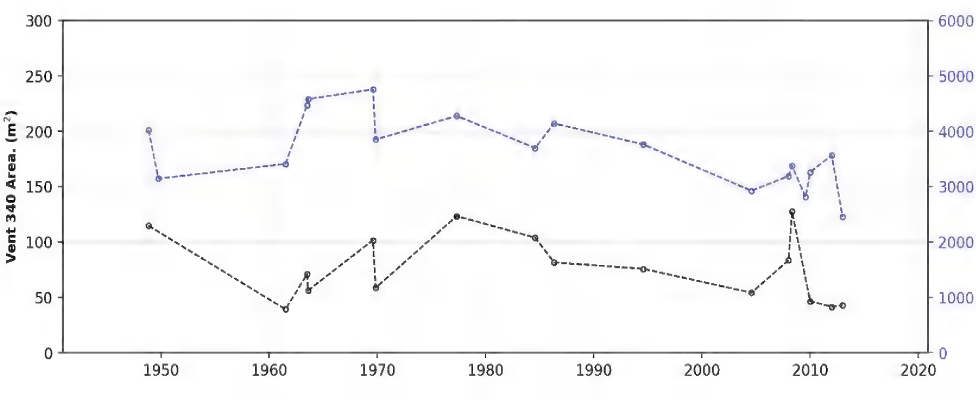


Figure 7. Wetland area mapped from aerial photography at the Lucky Last spring complex.



Influences on Wetland Dynamics

The water balance and, therefore, the observed dynamics in the wetland extent and discharge regime are influenced by stressors both hydrological – rainfall variability, groundwater recharge and abstraction – and non-hydrological, such as land use changes. Understanding the drivers of hydrogeological changes provides the basis for more meaningful analysis of temporal ecological datasets collected at spring wetlands. The detailed analysis of monitoring data and site conceptualisations highlight that the following elements are important for understanding temporal and spatial variability in wetland dynamics.

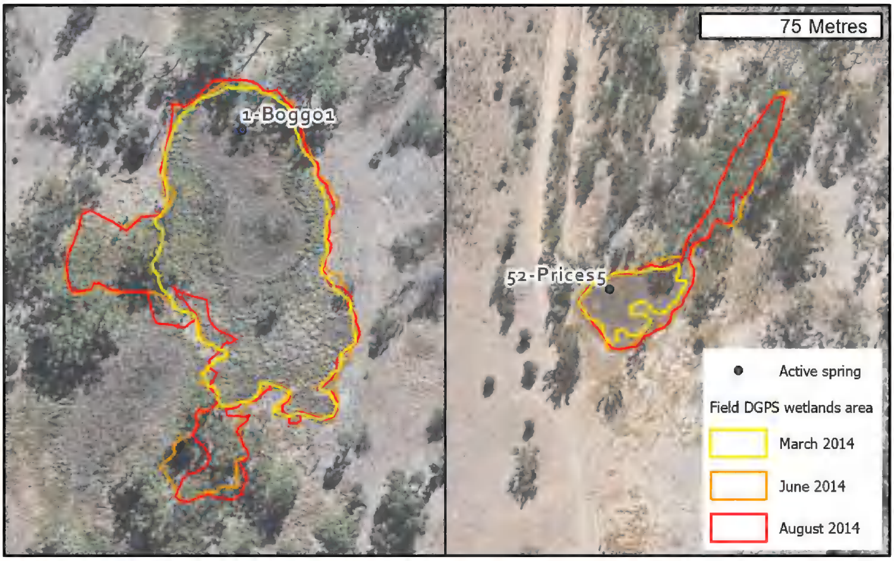
Topographic and Landscape Setting

Topographic setting refers to the position of the wetlands within the local relief. It provides an insight into the potential influence of local flow systems (via groundwater and/or surface runoff) on the hydrological regime at the wetland. For example, wetlands located in topographic lows or depressions are likely to receive surface runoff and discharge from local groundwater flow systems.

Spring wetlands in the Surat CMA are predominantly riverine (in a watercourse) or palustrine (vegetated, non-watercourse). Riverine wetlands, by definition, occur on the valley floor. Palustrine wetlands may occur in topographic lows, on slopes, or at the break of a slope. Some wetlands are considered palustrine even if they receive intermittent inflows from flooding, but their dominant water source and the reason for their occurrence is groundwater discharge. The primary distinction between wetlands, therefore, is whether they occur within riverine settings and are influenced by surface water inflows in addition to groundwater discharge.

In terms of seasonal dynamics and wetland geometry, wetlands located on slopes in the Surat CMA are likely to form discharge tails. At these wetlands, seasonal dynamics are more apparent than those positioned on more even ground. This is interpreted to primarily be a response to seasonal changes in evapotranspiration, with components of the wetland water budget transitioning from evapotranspiration to physical groundwater discharge from the wetland. In most cases, groundwater pressure in the vicinity of the wetland remains relatively stable. This is shown in Figure 8 with two wetlands, in different landscape settings, at the Boggomoss spring complex near Taroom.

Figure 8. Variations in extent at Wetland 1 (a circular flat wetland located on the flat) and Wetland 52 (on a slight slope with large increase in wetted area during autumn months) (Lyons et al., 2015; OGIA, 2015a).



Geomorphology

The geomorphology and substrate of wetlands can significantly influence the wetland dynamics. Geomorphology refers to the current landscape evolution processes of the wetland setting, and whether they are predominantly erosional or depositional in nature. Substrate refers to the base material in which the wetland has formed, within the broad categories of soil, rock or colluvial/alluvial material.

These attributes collectively describe the stability of the landforms in which wetlands are located and the likelihood of change in the wetland form over shorter geomorphological time scales (months to years) due to landform evolution processes. Alluvial and colluvial substrates are considered the least geomorphologically stable. Rock is considered to be the most stable, although grazing and vegetation management can affect the stability at sites regardless of landform.

In the Surat CMA, the majority of wetlands are located in erosional landscapes, exacerbated by land use change and grazing. The wetlands in the depositional environment of the Dawson River are the exception. In terms of substrate, most wetlands are located in soil, with the exception of some spring complexes located along the mid to upper tributaries of the Dawson River.

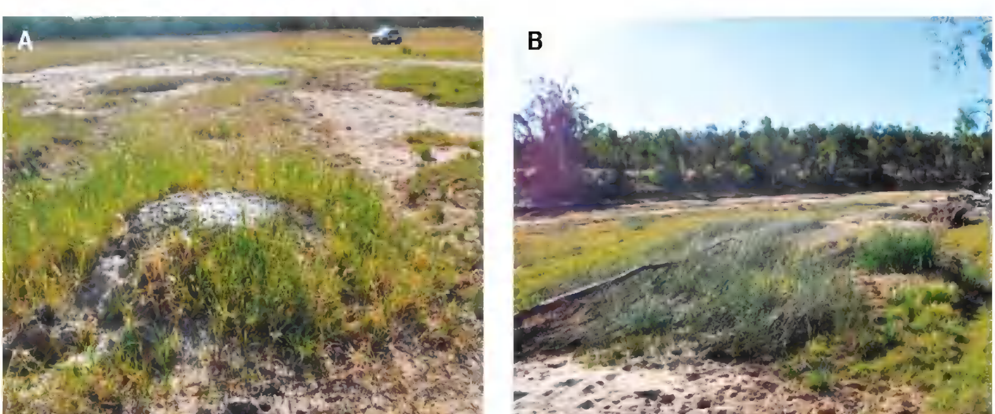
In a depositional environment, sedimentation and deposition may influence the wetland extent, in the absence of a change in the underlying groundwater flow regime. Similarly, within an erosional environment, changes to the geometry of a wetland can occur over short timeframes. Figure 9 provides an example of wetlands within different geomorphological settings.

Regolith and Soils

In the context of spring wetlands, regolith is the material in which a wetland occurs that has been altered by the physical, biological and chemical processes associated with groundwater discharge and the associated ecology. It includes the weathered substrate – the soil found within the wetland – and comprises inorganic and organic material to varying degrees. It forms an important aspect of wetland functioning, in that it influences the water-holding capacity of the wetland and the type of vegetation supported. It is noted that there is a feedback loop between regolith and ecology, with each influencing the other.

Regolith depth varies between wetlands, with deeper profiles of at least 5 m noted at many complexes including Boggomoss, Scott's Creek and Elgin 2. At these complexes, the wetlands can hold a greater quantity of water in proportion to their cross-sectional area and therefore are more likely to support a greater biomass of vegetation and may have greater resilience to short-term hydrologic changes. Elsewhere, the regolith depth is shallow. This has important implications for understanding wetland dynamics and the drying and wetting cycles at these wetlands.

Figure 9. (A) Spring wetlands north-east of Injune (Abyss) within an erosional environment. (B) wetlands within a depositional environment (Scott's Creek).



Mounded regolith features are a distinguishing characteristic of a number of wetlands. These mounds are interpreted to have formed primarily in response to biological processes in which organic matter builds up over time due to the decomposition of wetland vegetation, as opposed to the precipitation of solutes emanating from groundwater discharge. The growth of mounded features may also be accentuated by the erosion of the surrounding landscape.

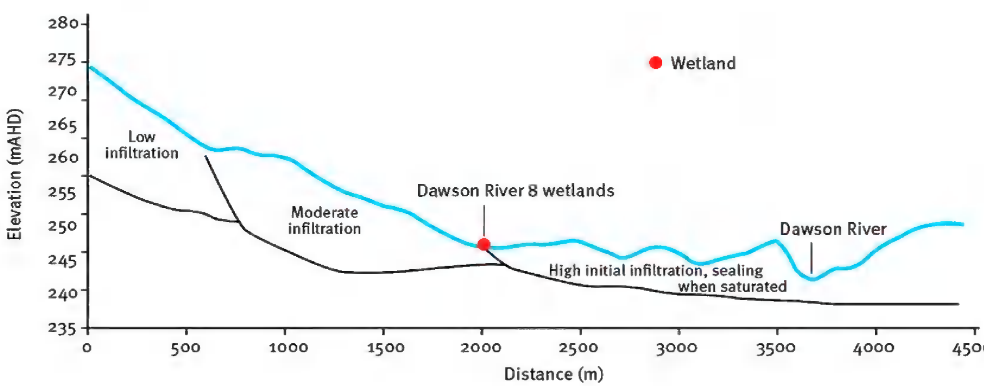
Figure 10 provides an example of the importance of understanding the interplay between topography, surrounding soils and their properties. These elements significantly influence local groundwater recharge and discharge characteristics and, in many cases, the wetland geometry, due to slope and the hydraulic properties of the surrounding soils. In this example, the soils of the upper water catchment are relatively well drained, with the infiltration rate of the floodplain soils decreasing upon saturation, resulting in confining properties. The expansion and reduced hydraulic conductivity of the soils immediately surrounding the wetlands results in discrete discharge features.

In other parts of the GAB, the immediate regolith and surrounding soils significantly influence dynamics of the wetland area. In the South Australian portion of the GAB, travertine mounds occur at many springs. At these locations, as groundwater rapidly discharges to the surface, the drop in pressure between the surface and subsurface environments causes calcium carbonate in solution to precipitate. Precipitation is facilitated by calci-fixating cyanobacteria to form travertine. The formation of these features significantly influences the variability in extent and dynamics of these wetlands (Keppel et al., 2018).

Climate

Climatic variability has the capacity to influence spring wetlands in several ways: directly, through regional and local groundwater recharge to a spring's source aquifer, direct rainfall infiltration to the wetland and seasonal cycles of evapotranspiration from the wetland; and indirectly, through increased groundwater abstraction and grazing pressure on the wetland.

Figure 10. Land system and dominant soil types at Dawson River 8 spring complex (adapted from Speck et al., 1968 and SKM, 2014).



Land System	Wondoan Undulating Brigalow plains		Coolibah Flooded alluvial country with coolibah	
Unit	Mild colluvial slopes Units 5,6,7, deep contars textured soils	Colluvial and Alluvial slopes Units 10, deep racking clays	Black flood plains, Unit 10 cracking clays	Channel System
Soils	Vetisols and Dermisols High sodicty and low saturated permeability	Yellow grey well drained Sodols. Moderately drained, permeability decreases with depth	Vertisols Non sodic (except sands within channel) at surface cracking clays Permeability decreases with depth	
Geology	Birkhead Formation			Hutton Sandstone

Wetlands in the study area predominantly receive groundwater flow from regional groundwater flow systems. In these aquifers, groundwater has travelled a significant distance from the aquifer recharge zone. Variations in longer-term rainfall patterns and associated recharge are often observed in groundwater monitoring bores located in areas of recharge. However, there is often limited groundwater monitoring infrastructure in the vicinity of spring wetlands, particularly across the historical time period, to utilise groundwater monitoring data in understanding aquifer behaviour at the spring. Until the more recent period, the selection of groundwater monitoring locations has primarily been driven by water resource development requirements.

Groundwater Abstraction

There are approximately 22,300 water supply bores in the Surat CMA. Of this number, approximately 8000 are accessing formations of the Surat Basin, 600 in the Bowen Basin, while the remainder – approximately 13,700 – are screened in the overlying shallow alluvium and basalt (UWIR, 2019). Most water supply bores – approximately 90% – are constructed to depths of less than 200 metres. At these depths, sufficient supplies are generally available for stock and domestic purposes.

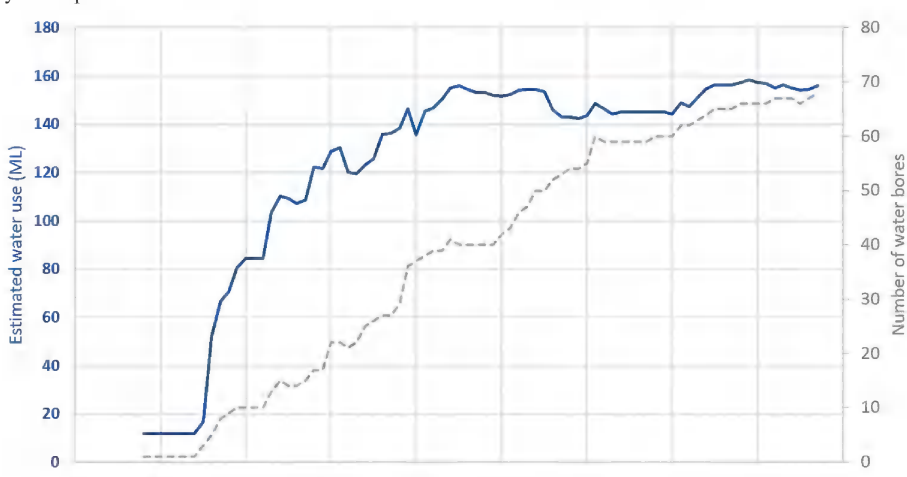
In the Surat CMA, spring wetlands are also predominantly located on the margins of the sub-basins and are fed by aquifers at depths of less than 100 m (Figure 3). Historically, water supply bores were often located near springs, as they were known to be high-potential water supply locations.

A significant challenge is understanding the historical groundwater extraction and resulting changes in groundwater pressure in the vicinity of the springs. In terms of wetland dynamics, it is important to conceptualise pre-development conditions and how the wetland may have changed through time in response to a potential reduction in groundwater pressure and implications for the wetland area.

In the absence of historical groundwater pressure monitoring, Figure 11 – showing the growth in water supply bores and water use (OGIA, 2019) within 10 km of springs sourced from the confined Hutton Sandstone – is used as a proxy for water use changes over time.

As shown, there was expansive groundwater development from the 1940s through to the 1980s, since which time bore development has stabilised. It is likely that groundwater levels have declined in response to this development in the vicinity of these springs. This is broadly consistent with the period of development across much of the Surat Basin. This provides an indication of growth and may be useful for correlation with changes in wetland extent in the absence of groundwater pressure data.

Figure 11. Time series of water bore development in the Hutton Sandstone, within 10 km of two spring complexes fed by this aquifer – Scott's Creek and Dawson River 8.



Land Use

Land use can influence the observed wetland extent, the overall condition of the wetlands and their seasonal and long-term dynamics. In the Surat CMA, observed effects of grazing activities include compaction, disturbance and changes in the wetland water chemistry. Pugging around the edges of mounded spring wetlands can create small drains, which alter the area of saturated soil. Within the wetland, conceptually, this could increase areas of ponding, increasing evaporation, which may result in elevated conductivity within the wetland. Grazing of wetland vegetation alters the balance between evaporation and transpiration within the wetland in addition to nutrient loads. The indirect effects of changes in land use can have long-term impacts on wetland area and condition.

Integrating Science with Management

The growth in the CSG industry and other water extraction in the Surat CMA required the rapid advancement in knowledge and understanding about springs, to inform the assessment of impacts and the development of monitoring approaches to further understand baseline conditions and to hypothesise their response to change.

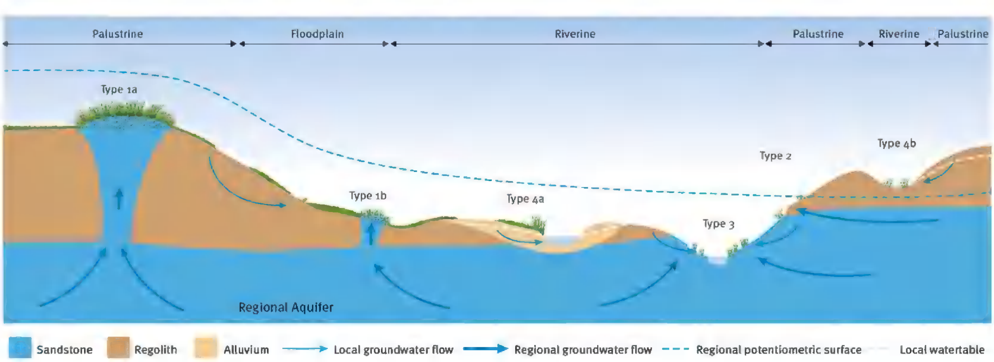
Ecohydrogeological data collected through targeted field surveys provided the basis for the initial assessment of likelihood and consequence of impact. Hydrogeological conceptualisation and the detailed assessments of wetland attributes informed the development of a spring typology (OGIA, 2016) to support risk assessment and guide monitoring and management arrangements (Figure 12) – including four spring types. Attributes are selected as the key differentials in describing how the wetlands occur within the landscape and how they are likely to respond to a change in the groundwater regime connected to the wetland.

Importantly, this approach provides a direct linkage between detailed hydrogeological conceptualisation and a tool to guide a specific management requirement. In other parts of the GAB, such as in South Australia, springs have also been classified to support the assessment of risk and decision making (Green et al., 2013). Since then, building upon this work and in response to potential CSG development, local-scale assessments have been completed to inform specific management questions in South Australia (Gotch et al., 2015). More recently, whole-of-basin approaches are being developed, including the GAB springs adaptive management plan (Brake, 2020), which seeks to bring together the current science to improve the on-ground management of GAB springs.

In all cases, to support a specific management requirement, the currently available science has been integrated and presented in a manner to support decision making. In parallel, knowledge continues to evolve. In the case of the Surat CMA, the periodic assessment (every three years) provides the opportunity to continue to advance knowledge and provide a direct linkage to management arrangements.

Ongoing advances in spring monitoring design, based on current knowledge, are necessary to continue to build and refine understanding about natural variability in spring discharge, and to confirm or amend the hydrogeological conceptualisation and water balance.

Figure 12. Wetland typology developed to inform management arrangements in the Surat CMA.



Future research directions include targeted seasonal monitoring to better understand temporal dynamics of water flows; evaluation of techniques to improve the ability to monitor wetlands; integration of Indigenous knowledge of dynamics; and further investigation of historical aerial imagery and finer-scale remote sensing to elucidate spatial dynamics.

Conclusions

In response to rapidly advancing CSG development in the Surat and southern Bowen basins, detailed field surveys and hydrogeological conceptualisation have been completed since 2011 to provide foundational science for the management of potential impacts – spring location, source aquifer, values and natural variability in groundwater discharge. The approach of evolving the underpinning science to inform a specific management requirement is more broadly applicable to all groundwater-dependent ecosystems.

The ecology and processes that occur within wetlands intrinsically rely on the maintenance of the spring wetland water balance. Beyond the hydrogeological occurrence of the springs, quantifying the spatial and temporal dynamics of the wetland water balance requires site-specific data for each component. This is important, as ecological monitoring data and observed change can only be meaningfully analysed with an understanding of the wetland water balance and change in individual components. On the basis of the work completed in the Surat CMA, important factors to understand change are landscape setting, regolith and surrounding soils, climate and adjacent land use.

A significant challenge is the identification of the historical extent of wetlands and natural variability prior to groundwater development and landscape change. In this paper, opportunistically collected aerial imagery and characterisation of local groundwater development provide context for further understanding historical conditions. In more arid parts of the GAB, remote sensing has proved effective and a more distinct boundary between spring vegetation and the surrounding landscape can be achieved (White et al., 2016).

Importantly, in the Surat CMA, targeted research has been undertaken to inform a specific management requirement. Findings from research have been synthesised in technical reports, but also into management tools – such as the spring typology – which support the assessment of risks to springs and provide a basis for initial monitoring design. Critically, the underpinning legislative framework provides for an iterative cycle of research, monitoring and growth in knowledge, which directly inform revisions to management arrangements.

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Hydrochemistry Highlights Potential Management Issues for Aquifers and Springs in the Lake Blanche and Lake Callabonna Region, South Australia

Mark Keppel[1], Daniel Wohling[2], Andrew Love[3], and Travis Gotch[1]

Abstract

A hydrochemistry-based study has highlighted potential management implications for selected aquifers and springs located within the Lake Blanche and Lake Callabonna region in the far north of South Australia. The interpretation of hydrochemical and environmental tracers from 14 springs and 17 water wells, as well as historically available data, were used to establish five hydrochemical-based aquifer types for the region:

1. Fractured rock crystalline basement aquifer.
2. Patchawarra Formation (Cooper Basin) aquifer.
3. J-K aquifer (Algebuckina Sandstone, Cadna-owie Formation and lateral equivalents) of the Great Artesian Basin.
4. A sandstone unit or units interpreted to occur within the Neocretaceous Rolling Downs Group, which is informally termed the 'Rolling Downs Group sandstone (RDGS) aquifer'.
5. Cenozoic aquifer.

Two key findings from this study have potential implications for ongoing resource management. First, artesian groundwater conditions were identified for the first time within sandstones found within the Neocretaceous confining layer (the RDGS aquifer). Although the exact stratigraphic nomenclature of this sandstone unit is not yet confirmed, groundwater sourced from this unit is currently being used for stock. Second, the RDGS aquifer may contribute to spring flow at Lake Blanche and Lake Callabonna. Similarly, the fractured rock aquifer may be a source of water for the Petermorra Springs complex. Beyond certain results from these three spring complexes, the majority of hydrochemical and environmental tracer analyses infer that the J-K aquifer is the primary source aquifer supporting spring flow.

Keywords: springs, South Australia, hydrochemistry, Great Artesian Basin, Cooper Basin

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Introduction

The effective management of spring-supported environments requires a clear understanding of the groundwater source and system that supply them. The potential for petroleum hydrocarbon developments within the Weena Trough of the southern Cooper Basin prompted a need to understand the source of flow to the springs within the Lake Blanche and Lake Callabonna region of South Australia (Harrington & Harrington, 2015). There have been numerous studies characterising the groundwater sources for various Great Artesian Basin (GAB) spring complexes within South Australia (e.g. Dalla Valle, 2005; Love et al.,

2013; Harrington & Harrington, 2015; Keppel et al., 2015), although there remains some uncertainty as to the groundwater source for some of these complexes. This uncertainty has implications for water allocation and groundwater resource management.

By extension, understanding the responses to and impacts on spring flows from any water extraction associated with potential petroleum hydrocarbon developments within the southern Cooper Basin, which underlies the major aquifers of the GAB and the Lake Eyre Basin in the region, is critical for planning, regulatory and management purposes (Harrington & Harrington, 2015).

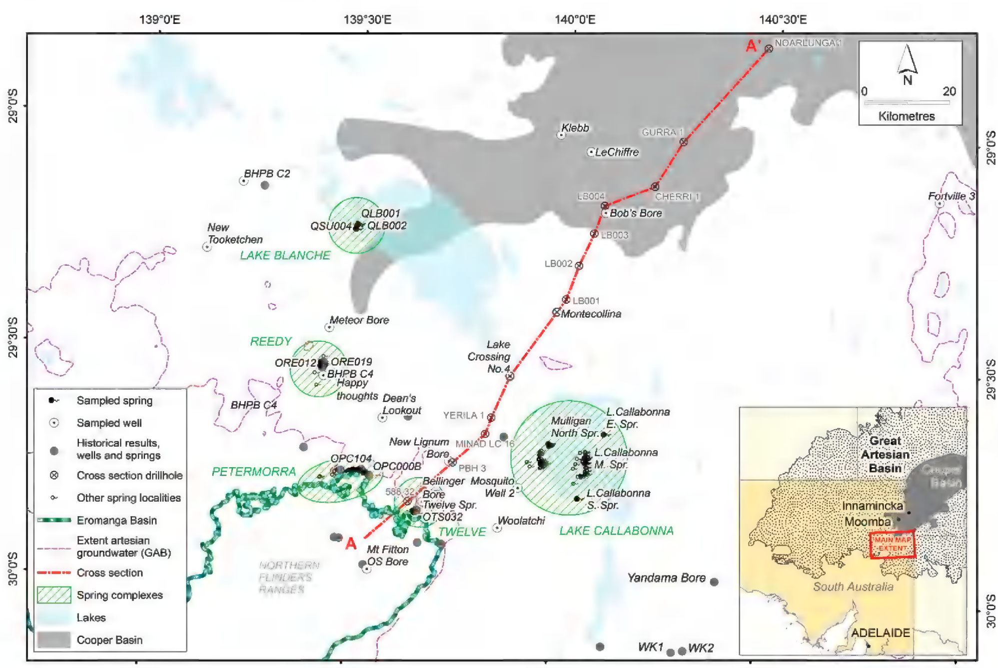
The objective of this study was to provide an initial description of the primary groundwater source for springs within the Lake Blanche and Lake Callabonna region based on hydrochemistry data, and to determine what implications the conclusions may have for the ongoing management of the groundwater resource. Groundwater hydrochemistry and environmental tracers provide a reliable methodology to identify the groundwater source and therefore provide a line of evidence for identifying the likely source of groundwater supporting spring flow.

Materials and Methods

Location and Physiography

The investigation area is approximately 600 km north-north-east of Adelaide and covers approximately 15,100 km^2 extending from the northern Flinders Ranges in the south, past Lake Blanche to the southern Cooper Basin in the north, and east to Lake Callabonna (Figure 1). The area comprises five spring complexes: Lake Blanche, Reedy, Petermorra, Twelve and Lake Callabonna, all of which are part of the Lake Frome Springs supergroup. According to Gotch (2013), a spring complex is a cluster of spring groups that share similar geomorphological settings and broad similarities in water chemistry, whereas a supergroup is a cluster of spring complexes. Finally, Gotch (2013) defines a spring group as clusters of springs that share similar water chemistry and source their water from the same fault or other structure.

Figure 1. The study area and hydrochemistry sampling sites.



The climate is generally arid, with weather patterns dominated by persistent high-pressure systems. Rainfall comes predominantly from weak winter cold fronts originating in the Southern Indian Ocean, or sporadic summer monsoon rainfall originating in north-west and north-east Australia. Rainfall for the nearest weather station at Moomba averages 170 mm/year (BoM, 2019), although this can vary significantly from year to year. Since 1996, annual rainfall has varied from 43 mm/year to 660 mm/year.

Given the arid climate, aeolian-driven erosion as described by Mabbutt (1977) is important in shaping the physiography of the region. The landscape is predominantly flat desert consisting of sand dunes and gibber plains. Exceptions to this include the northern Flinders Ranges, a mountain range comprising outcropping basement rocks that are Archean to Cambrian in age, and silt and clay pans associated with Lake Blanche and Lake Callabonna, found along the northern and eastern margins of the study area (Figure 1).

The largest town near the study area is Moomba, with a population of approximately 1200, largely composed of itinerant petroleum industry workers. Innamincka, located to the north of the study area, has a population of 43 (ABS, 2016). Parts of the Pirlatapa, Wadigali, Dieri, Yawarrawarrka and Adnyamathanha Aboriginal language groups occur within the study area.

Methodology

Hydrochemistry and environmental tracer data from 14 springs and 17 wells were collected between 5 and 11 June 2015, and 25 and 28 August 2015 (Keppel et al., 2016; Harrington & Harrington, 2015). Where possible, wells where the hydrostratigraphy of the completion interval was known were targeted for sampling. Four aquifer types were targeted during the field work campaign:

- Fractured rock (Precambrian crystalline) basement aquifer.
- Patchawarra Formation (Cooper Basin) aquifer.
- Cadna-Owie Formation – Algebuckina Sandstone (and lateral equivalents) aquifer (referred to here as the J-K aquifer).
- Cenozoic aquifer.

These aquifers are presented in cross-section in Figure 2. The hydrostratigraphic nomenclature presented here represents a simplified version of the stratigraphy present in the study area. A summary of stratigraphy for the study area is presented in Table 1, which will aid the placing of the hydrostratigraphy discussed into a wider geological context.

Analytes measured during this investigation include:

- The major ions chloride (Cl^-), sulphate (SO_4^{2-}), sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) and alkalinity (as HCO_3^-). Results were rejected if charge balances for major ions were ±5% or greater. The minor ions fluoride (F^-), bromide (Br^-) and strontium (Sr^{2+}) were also analysed.
- The stable isotopes of the water molecule deuterium (δ^2H), oxygen-18 ($\delta^{18}O$).
- The isotopic strontium ratio ($^{87}Sr/^{86}Sr$).
- Radiocarbon (^{14}C) expressed as percent modern carbon (pMC).
- Chlorine-36 ($^{36}Cl/Cl$).

Scatter plots and a Piper diagram were used to determine broad hydrochemical characteristics of the groundwater and interpret the data in relation to important hydrochemical processes.

The stable isotopes of the water molecule, deuterium (δ^2H) and oxygen-18 ($\delta^{18}O$), were compared to the local meteoric water line (LMWL) for Alice Springs (Crosbie et al., 2012; IAEA, 2013) to determine the effects of evaporation or mixing on groundwater samples. The LMWL is derived from precipitation collected from a single site or set of 'local' sites (USGS, 2004). Groundwater that has evaporated or mixed with evaporated water typically plots below the LMWL, along lines that intersect the LMWL at the location of the original unevaporated composition of the water (Craig, 1961; USGS, 2004). The LMWL at Alice Springs was favoured over Woomera (the nearest town to the investigation area where stable isotopes in precipitation have been recorded) because of a limited stable isotope record at Woomera (Liu et al., 2010).

Isotopic strontium ($^{87}Sr/^{86}Sr$) was used as a means of discriminating between source aquifers on the basis that the mineralogy of each aquifer may potentially impart a unique $^{87}Sr/^{86}Sr$ signature. Analysis of $^{87}Sr/^{86}Sr$ allows groundwater end-members, mixing trends and the influence of

mineral precipitation or evaporation to be identified. Shand et al. (2009) state that strontium is a divalent ion that shows similar geochemical properties to calcium (Ca) and therefore readily substitutes for calcium in minerals. Shand et al. (2009) also note that the isotopic abundance in rocks may vary due to the formation of ^{87}Sr by the decay of naturally occurring rubidium-87 (^{87}Rb).

Consequently, the mineralogy and age (to allow for the decay of ^{87}Rb) of rocks in an aquifer are important controls on the variation of ^{87}Sr and ^{86}Sr. By extension, Shand et al. (2009) and Aberg et al. (1989) described differences in the variations in the ratio of ^{87}Sr to ^{86}Sr in groundwater as a sum of atmospheric inputs, mineralogy along the flow path, mineral dissolution, ion exchange characteristics and residence time. Consequently, the $^{87}Sr/^{86}Sr$ ratio is useful for identifying groundwater mixing or exchange between different aquifer sources. A useful means of discriminating between different processes, such as mixing of groundwater with multiple $^{87}Sr/^{86}Sr$ signatures, evaporation, dilution, exchange or mineral precipitation, is to plot ^{87}Sr and ^{86}Sr data against the reciprocal of Sr^{2+} (1/Sr) (Shand et al., 2009). Shand et al. (2009) state that mineral precipitation and concentration via evaporation should not modify the Sr isotope ratio in water. However, mixing between two end-member waters with differing Sr isotopic ratios will result in a gradation of ratio values, whereas mineral dissolution and exchange are likely to change the Sr isotopic ratio depending upon the isotopic composition of the reacting phase. The most common mineral involved with respect to modification of Sr concentration, and by extension the $^{87}Sr/^{86}Sr$ signature of a water, is calcite due to the substitution of strontium for calcium.

Carbon-14 (radiocarbon) and chlorine-36 ($^{36}Cl/Cl$) are routinely used to estimate the apparent age of groundwater, as long as initial conditions at the time of recharge and additional sinks or sources can be reasonably estimated or excluded. However, for this study, no apparent age or correction calculations were applied to either the radiocarbon or $^{36}Cl/Cl$ ratio; instead, the uncorrected radiocarbon (as percent modern carbon, pMC) and $^{36}Cl/Cl$ ratio results provide a relative indication of apparent groundwater age differences between samples and identify possible mixing.

Figure 2. Interpreted cross-section through study area (A to A'), showing general stratigraphy.

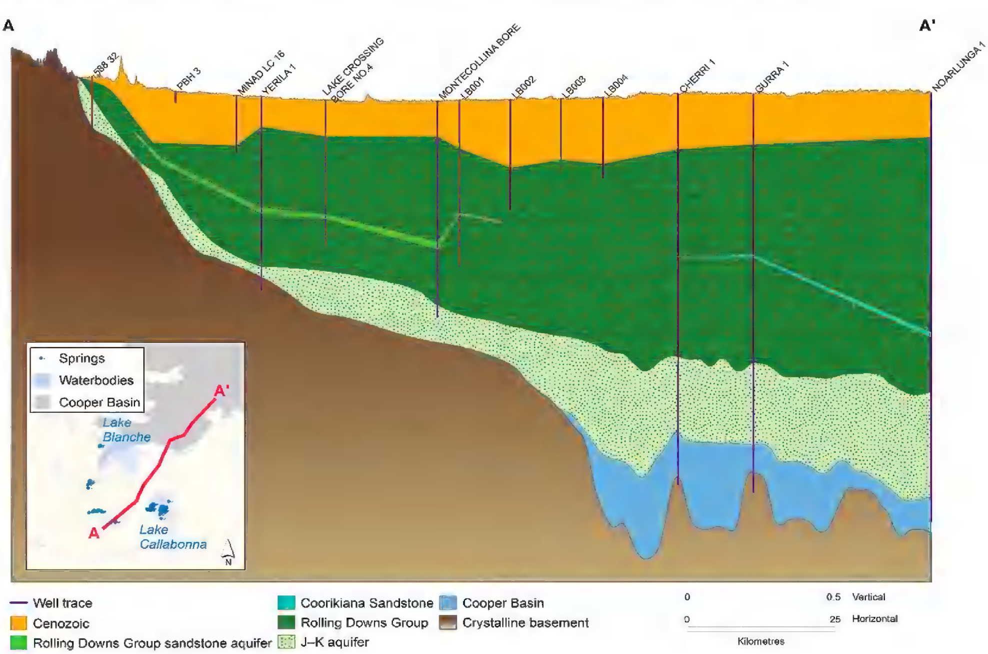


Table 1. Stratigraphy of the study area (after DMITRE, 2012; Krieg et al., 1995; GA, 2015; and Fry, 2014).

Period	Basin	Group name	Formation names	Lithology description	Depositional environment	Hydrogeological characteristics
Cenozoic	Lake Eyre		Coonarbine Formation Eurinilla Formation Millyera Formation Willawortina Formation Cadelga Limestone Doonbara Formation Namba Formation Etadunna Formatiom Cordillo Silcrete Eyre Formation Mount Sarah Sandstone	Sand, conglomerate, clay, gypsiferous, ferruginous and siliceous overprints.	Aeolian, alluvial, fluvial, lacustrine, regolith overprints.	Mainly aquifer with interbedded confining layers.
Cretaceous	Eromanga (GAB)		Winton Formation Mackunda Formation	Shale, siltstone, sandstone, minor coal.	Fluvial, lacustrine, subtidal marine, shoreline.	Confined minor aquifers.
Cretaceous	Eromanga (GAB)	Rolling Downs Group	Oodnadatta Formation Coorikiana Sandstone Bellinger Sandstone Bulldog Shale	Claystone, mudstone and shale. Minor sindstone and siltstone.	Low-energy marine. Sandstone units indicative of higher energy deposition.	Confining layer. Sandstone units can form aquifers (RDGS aquifer).
Cretaceous-Jurassic	Eromanga (GAB)		Cadna-owie Formation Parabarana Sandstone Algebuckina Sandstone (Namur, Adori and Hutton sandstones, Murta, Westbourne, & Birkhead formations in Cooper Basin region)	Fine- to coarse-grained sandstone.	Fluvial, lacustrine to marginal marine.	Aquifer. Some intra-aquifer confining layers in Cooper Basin region.

Period	Basin	Group name	Formation names	Lithology description	Depositional environment	Hydrogeological characteristics
Triassic	Cooper	Nappamerri Group	Cuddapan Formation Tinchoo Formation Arrabury Formation	Red beds, mudstone, siltstone, sandstone, lithic sandstone, coal beds.	Floodplain, meandering and braided alluvial, fluvial and lacustrine.	Sandstone units are aquifers. Others considered confining layers.
Permian-Carboniferous	Cooper	Gidgealpa Group	Toolachee Formation Daralingie Formation Roseneath Shale Epsilon Formation Murteree Shale Patchawarra Formation Tirrawarra Sandstone Merrimelia Formation	Sandstone, siltstone, coal, conglomerate.	Fluvio-deltaic, fluvio-glacial, paludal, lacustrine.	Sandstone units are aquifers. Others considered confining layers.

Results

Five hydrochemical-based aquifer types were identified. These aquifer types generally coincide with the four aquifers targeted at the commencement of the study; however, the identification of a fifth aquifer type, the RDGS aquifer, was an unexpected result. Likewise, the hydrochemical-based evaluation identified that Montecollina Bore (screened within the J-K aquifer) had a potentially damaged casing which is leaking water from the RDGS aquifer (Keppel et al., 2016).

A summary of the hydrochemical characteristics of each aquifer type is provided in Table 2.

Water Quality and Major Ions

Field water quality parameters are provided in Table 3, whereas Table 4 provides laboratory analyses for major ion and trace elements. The major ion and trace element analyses obtained during this study are supplemented by additional historical results sourced from Radke et al. (2000), Crossey et al. (2013), Priestley et al. (2013), Mahara et al. (2009) and the South Australian Government online database *Waterconnect* (www.waterconnect.sa.gov.au).

The groundwater sample collected from the fractured rock basement aquifer within the investigation area is mildly saline, with electrical conductivity (EC) of approximately 4500 µS/cm (Table 3). With consideration of historical results, the major ion hydrochemistry of the fractured rock aquifer groundwater can be described as Na^+ + (Ca^{2+} + Mg^{2+}) + Cl^- + SO_4^{2-} dominant (Figure 3).

Of note are the high concentrations of Mg^{2+} and, to a lesser extent, SO_4^{2-} and Ca^{2+} compared to other groundwater types (Figure 4A, B and C; Table 4). This is particularly evident when the ratio of these major ions against Cl^- (as a proxy for overall salinity) are compared (Figure 4D, E and F). Concentrations of Mg^{2+} (Figure 4A), Ca^{2+} (Figure 4B), K^+ (Figure 5A) and HCO_3^- (Figure 5B) appear to be independent of overall salinity, in contrast to concentrations of SO_4^{2-} (Figure 4C) and Na^+ (Figure 5C). Elevated Mg^{2+} and Ca^{2+} concentrations are interpreted as indicators of dolomite dissolution, whereas elevated SO_4^{2-} concentrations are interpreted to be a result of sulphides in basement rocks. Comparison of Na^+ results with the expected seawater concentration suggests a marine aerosol source (Figure 5C).

The two groundwater samples collected from the Patchawarra Formation are brackish and generally more saline than the majority of other groundwater samples, with EC varying between 5000 and 6000 µS/cm (Table 3). In contrast,

groundwater from the J-K aquifer is fresh to brackish, with EC varying between 2000 and 6100 µS/cm (Table 3). The major ion hydrochemistry types of the Patchawarra Formation and the J-K aquifer are similar and predominantly Na^++ HCO_3^- + (Cl^-) (Figure 3). Typically, Na^+ constitutes >90% of the proportional cation concentration, whereas the proportional concentration of HCO_3^- ranges between 30% and 90%, although typically greater than 50% (Figure 3). Additionally, relative concentrations of SO_4^{2-} are very low compared to groundwater from other aquifers, and are typically less than 5%. This contrast in proportional major ion concentration between the Patchawarra Formation and J-K aquifer and other groundwater types from the area of investigation is particularly evident in the Na^+/Cl^- and HCO_3^-/Cl^- ratios (Figure 5E; Figure 5F). Figure 5E and Figure 5F highlight a clear 1:1 relationship between Na^+ and HCO_3^- in groundwater from the Patchawarra Formation and the J-K aquifer which is not apparent in groundwater from other aquifers.

Figure 3. Piper diagram displaying major ion results from the investigation area.

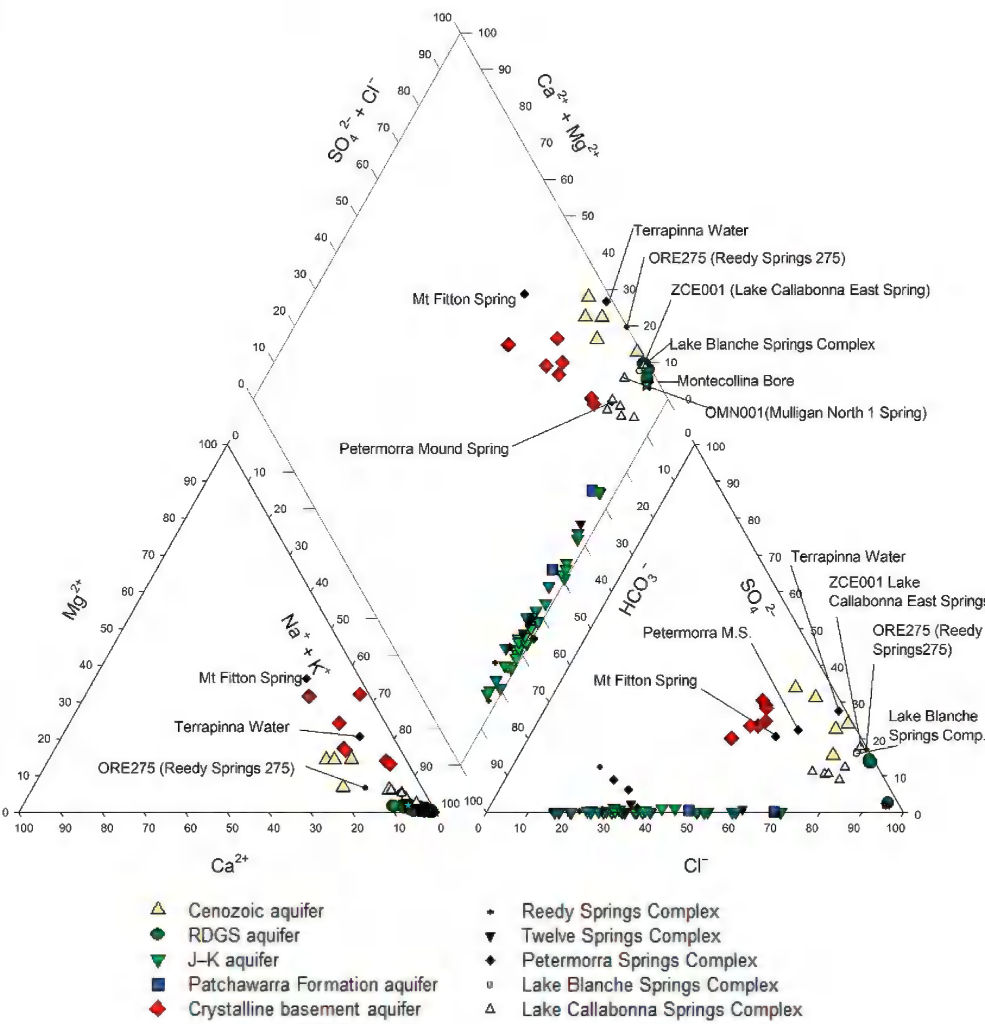


Table 2. Summary of hydrochemical characteristics for the investigation area.

Hydrogeological group	Major ions	Stable isotopes of water	$^{87}Sr/^{86}Sr$	Radiocarbon and $^{36}Cl/Cl^-$
Fractured rock basement	$Na^+ + (Ca^{2+} + Mg^{2+}) + Cl^- + SO_4^{2-}$	Depleted compared to Cenozoic and RDGS aquifers. Comparable to J-K aquifer.	High compared to other types.	Relatively young age indicated. Comparable to Cenozoic aquifer groundwater.
Patchawarra Formation	$Na^+ + Cl^- (+ HCO_3^-)$ Elevated K^+ compared to other aquifer types	Depleted compared to all other groundwater types.	Relatively high compared to J and Cenozoic aquifers.	Relatively old age indicated. Comparable to J-K aquifer.
J-K aquifer	$Na^+ + HCO_3^- + (Cl^-)$	Depleted compared to Cenozoic and RDGS aquifers. Comparable to fractured rock basement aquifer.	Large range from 0.706 to 0.7195. Isotopic Sr range very narrow.	Oldest ages indicated compared to all other groundwater types.
RDGS aquifer	$Na^+ + Cl^-$	Enriched compared to J-K, Patchawarra Formation and fractured rock basement aquifers. Depleted compared to Cenozoic aquifers.	Low compared to J-K, Cenozoic and Patchawarra Formation aquifers. Comparable to seawater.	Younger age indicated compared to J-K and Patchawarra Formation aquifers but older than Cenozoic or fractured rock basement aquifer.
Cenozoic aquifer	$Na^+ + Cl^- + SO_4^{2-}$	Enriched compared to all other groundwater types.	Comparable to results found from J-K aquifer.	Youngest ages indicated compared to all other groundwater types.

Increases in concentration of Ca^{2+}, SO_4^{2-} and K^+ all appear to be independent of salinity as represented by Cl^- (Figure 4B; Figure 4C; Figure 5A), whereas Mg^{2+} appears to be only mildly correlated with salinity (Figure 4A). The ratio of Na^+ to Cl^- is larger than what might be expected from a source dominated by marine aerosols when compared with a trend line for seawater (Figure 5C).

Of note are the high concentrations of K^+ compared to Cl^- concentrations in the Patchawarra Formation, and compared to groundwater from other aquifers (Figure 5A; Table 4). Elevated K^+ concentrations from groundwater collected either from or near coal deposits have been previously noted in groundwater samples collected near Lake Phillipson (Keppel et al., 2015c).

Generally, F^- appears slightly elevated in the J-K aquifer compared to most other aquifer types, although both Bellinger Bore (10.3 mg/L) and Woolatchi Bore (9.0 mg/L) display notably elevated concentrations compared to other samples (Figure 6A; Table 4).

With respect to sources of salinity, the Br^-/Cl^- ratio is generally lower than expected from a marine aerosol source, with the ratio similar to those presented in Herczeg et al. (1991) for the western GAB. Herczeg et al. (1991) interpreted halite dissolution, most likely within the recharge area, as contributing to salinity (Figure 5D). Samples from the four easternmost wells (Fortville 3, WK2, WK3 and Yandama Bore, Figure 1) have a Br^-/Cl^- ratio closest to the seawater dilution line.

Table 3. Field water quality parameters.

Unit No.	Sample name	Aquifer	Field alkalinity (mg/L)	pH	Field EC (µS/cm)	Temperature (°C)
673800024	Happy Thoughts	Cenozoic	530	7.19	10086	21.5
683800013	New Lignum Bore	Cenozoic	184	6.74	7381	25.1
683800048	Mosquito Well 2	Cenozoic	206	7.03	5753	24.5
693900015	Bob's Bore	Cenozoic	97	6.47	16065	24.6
673800189	BHPB C4	J-K	726	7.12	2393	42.5
683800006	Lake Crossing No. 4	RDGS	88	7.30	23300	44.1
683900003	Montecollina	RDGS/J-K	157	7.48	17145	46.6
673900006	Meteor Bore	J-K	808	7.56	2745	40.5
673900016	BHPB C2	J-K	711	7.04	2188	40.8
673900034	New Toonketchen	J-K	616	7.47	2588	54.0
683800003	Dean's Lookout	J-K	436	7.54	4666	46.1
683800029	Woolatchi	J-K	538	7.47	4721	61.6
683800046	Bellinger Bore	J-K	628	7.50	2437	35.0
703900005	Fortville 3	J-K	851	7.02	6093	72.5
683900058	Klebb-1	Patchawarra Formation	1137	6.23	5257	32.3
693900031	LeChiffre	Patchawarra Formation	920	6.34	6002	22.4
683800037	Mt Fitton OS Bore	Fractured rock basement	419	6.91	4548	25.5
673800758	Reedy Spring 19 (ORE019)	Spring	714	7.30	1929	36.1
673801051	Reedy Spring 12 (ORE012)	Spring	1120	7.49	2093	19.7
673900031	Sunday Spring 4 (QSU004)	Spring	256	6.77	9322	21.4
683800001	Public House Spring 104 (OPC104)	Spring	730	7.60	1909	22.2
683800016	Mulligan Mid Spring 2 (OMM002)	Spring	291	7.00	4223	21.1
683800435	Public House Spring B (OPC000B)	Spring	699	7.81	2089	23.1
683800705	Twelve Spring 32 (OTS032)	Spring	618	7.53	1872	21.5
683800810	Mulligan Mid Spring 1 (OMM001)	Spring	312	7.07	3773	19.8

Unit No.	Sample name	Aquifer	Field alkalinity (mg/L)	pH	Field EC (µS/cm)	Temperature (°C)
683800833	Mulligan North Spring (OMN001)	Spring	—	7.12	6148	20.7
683900049	Lake Blanche Spring 1 (QLB001)	Spring	207	6.88	12949	19.3
693800072	Lake Callabonna South Spring 1 (ZCM001)	Spring	392	7.49	6258	16.3
693800081	Lake Callabonna East Spring 1 (ZCE001)	Spring	118	7.18	15553	19.3
693800117	Lake Callabonna Mid Spring 1 (ZCA001)	Spring	430	7.29	5692	15.6

Groundwater from the RDGS aquifer is saline compared to all other groundwater types. The EC varies between 17,000 and 23,000 µS/cm (Table 3), and the proportional major ion hydrochemistry is predominantly Na^++Cl^- (Figure 3; Table 4). Relative concentrations of Ca^{2+} + Mg^{2+} (<10%) and HCO_3^- (<5%) are very low, whereas SO_4^{2-} concentrations are less than 20%. Low concentrations of HCO_3^-, in absolute terms and as a proportion of total salinity compared to other groundwater types, are particularly notable and have an inverse relationship to salinity (Figure 5B). The Br^-/Cl^- ratio is similar to the J-K aquifer and generally lower than expected for a marine aerosol source; however, not so low as to suggest that the primary source of salinity is halite dissolution. Rather, mineral dissolution is thought to at least partially contribute to the salinity of the RDGS aquifer (Figure 5D).

Groundwater from the Cenozoic aquifer is brackish to saline, with the EC varying between 5700 and 16,000 µS/cm (Table 3). Proportional major ion hydrochemistry highlights a Na^+ + Cl^- + SO_4^{2-} dominant water type (Figure 3) which is interpreted to be predominantly derived from marine aerosols. There appears to be a trend toward Na^+ + Cl^- dominant major ion hydrochemistry, which is interpreted to be related to either the dissolution of halite or evapotranspiration based off Br^-:Cl^- ratios. Relative concentrations of SO_4^{2-} vary and are typically between 20% and 40%, whereas the relative concentrations of HCO_3^- are typically less than 10%. SO_4^{2-} concentrations appear to be slightly higher than other groundwater types (Figure 4F; Table 4). Additionally, and similar to the RDGS aquifer groundwater, concentrations of HCO_3^- also appear to have an inverse relationship to salinity as described by Cl^- (Figure 5B), which is in contrast to other major ions that appear to increase proportionally with increasing salinity (Figure 4; Figure 5).

Stable Isotopes Deuterium (δ^2H) and Oxygen-18 ($\delta^{18}O$)

Stable isotope results are provided in Table 5. Notably, stable isotope ratios from the Patchawarra Formation, J-K aquifer, fractured rock basement aquifer and RGDS aquifer plot close to the LMWL, indicating that there is little evaporative influence. The stable isotopes of water from these aquifers display a general trend towards enrichment, with samples from the Patchawarra Formation the most depleted, and being progressively more enriched through the J-K aquifer, to the fractured rock basement aquifer, to those from the RGDS aquifer (Table 5). Ratios vary from –8.0‰ to –6.27‰ for $\delta^{18}O$, and between –48.5‰ and –42.08‰ for δ^2H (Figure 6B).

In contrast, the stable isotope ratios for the Cenozoic aquifer are more enriched than samples from all other groundwater types. $\delta^{18}O$‰ ratios are between –5.56‰ and –4.24‰, and δ^2H‰ ratios between –40.4‰ and –34.4‰ (Table 5). Stable isotope ratios for the Cenozoic aquifer plot to the right of the LMWL on a slope indicative of an evaporative influence on the groundwater. The relative enrichment of the stable isotope composition found in the Cenozoic aquifer compared to other groundwater types is interpreted to be the influence of evapotranspiration on the composition of recharge waters in the local arid environment.

Figure 4. Scatter plots of (A) log Mg^{2+} versus log Cl^-; (B) log Ca^{2+} versus log Cl^-; (C) log SO_4^{2-} versus log Cl^-; (D) log Mg^{2+}/Cl^- versus log Cl^-; (E) Ca^{2+}/Cl^- versus Cl^-; and (F) log SO_4^{2-}/log Cl^- versus log Cl^- S.W. Seawater.

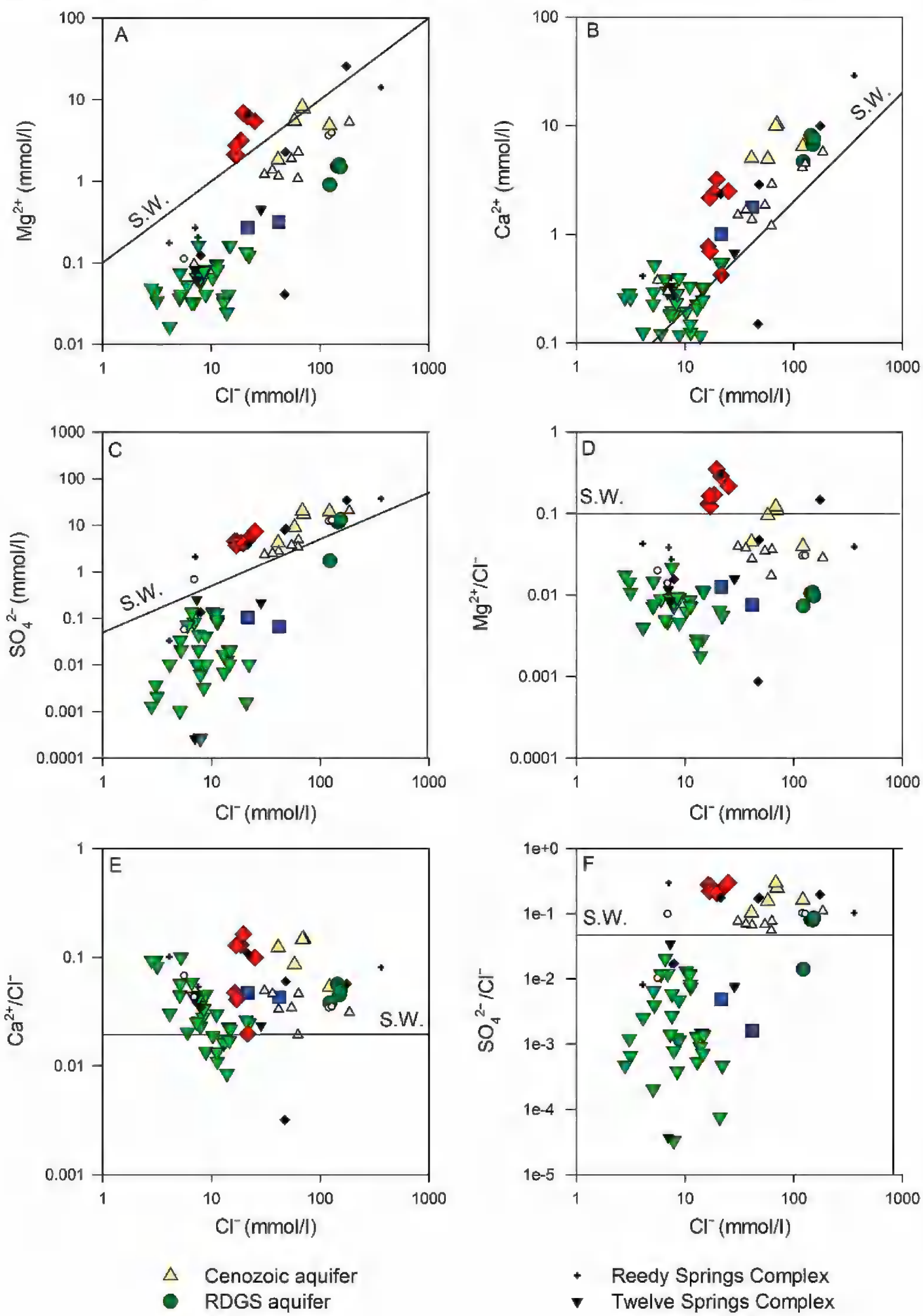


Figure 5. Scatter plots of (A) log K^+ versus log Cl^-; (B) log HCO_3^- versus log Cl^-; (C) log Na^+ versus log Cl^-; (D) log Br^-/Cl^- versus log Cl^-; (E) log HCO_3^- versus log Na^+; and (F) log HCO_3^-/Cl^- versus log Na^+/Cl^- S.W. Seawater.

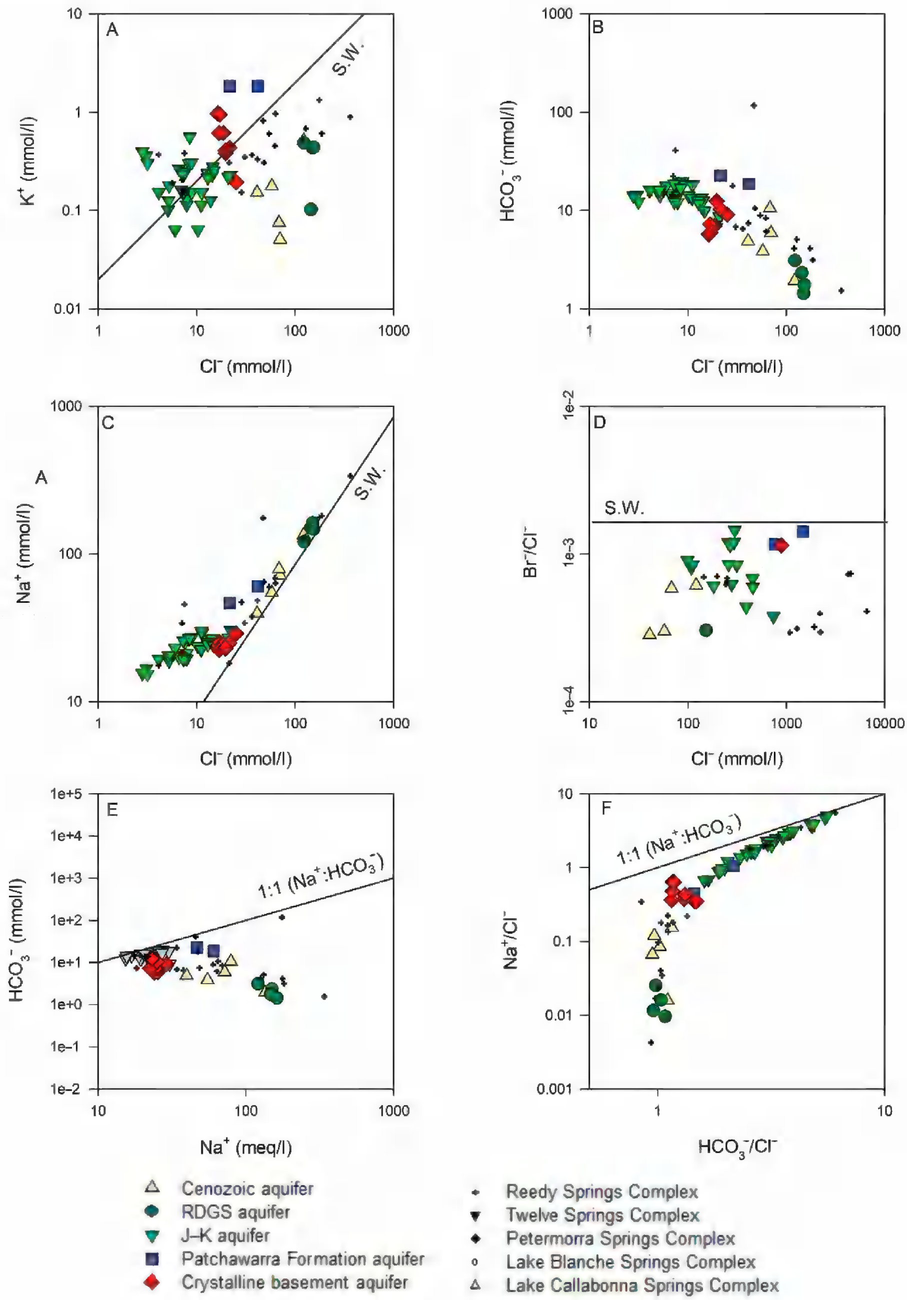


Figure 6. Scatter plots of (A) F^- versus Cl; (B) $^-$;δ^2H versus $\delta^{18}O$ ratios (C) $^{87}Sr/^{86}Sr$ versus 1/Sr; (D) $^{36}Cl/Cl^- \times 10^{-15}$ versus Cl^- (mg/L); (E) pMC (%) versus Cl^- (mg/L); (F) $^{36}Cl/Cl^- \times 10^{-15}$ ratios versus pMC. GMWL: global Mean Water line. LMWL: Local Mean Water Line.

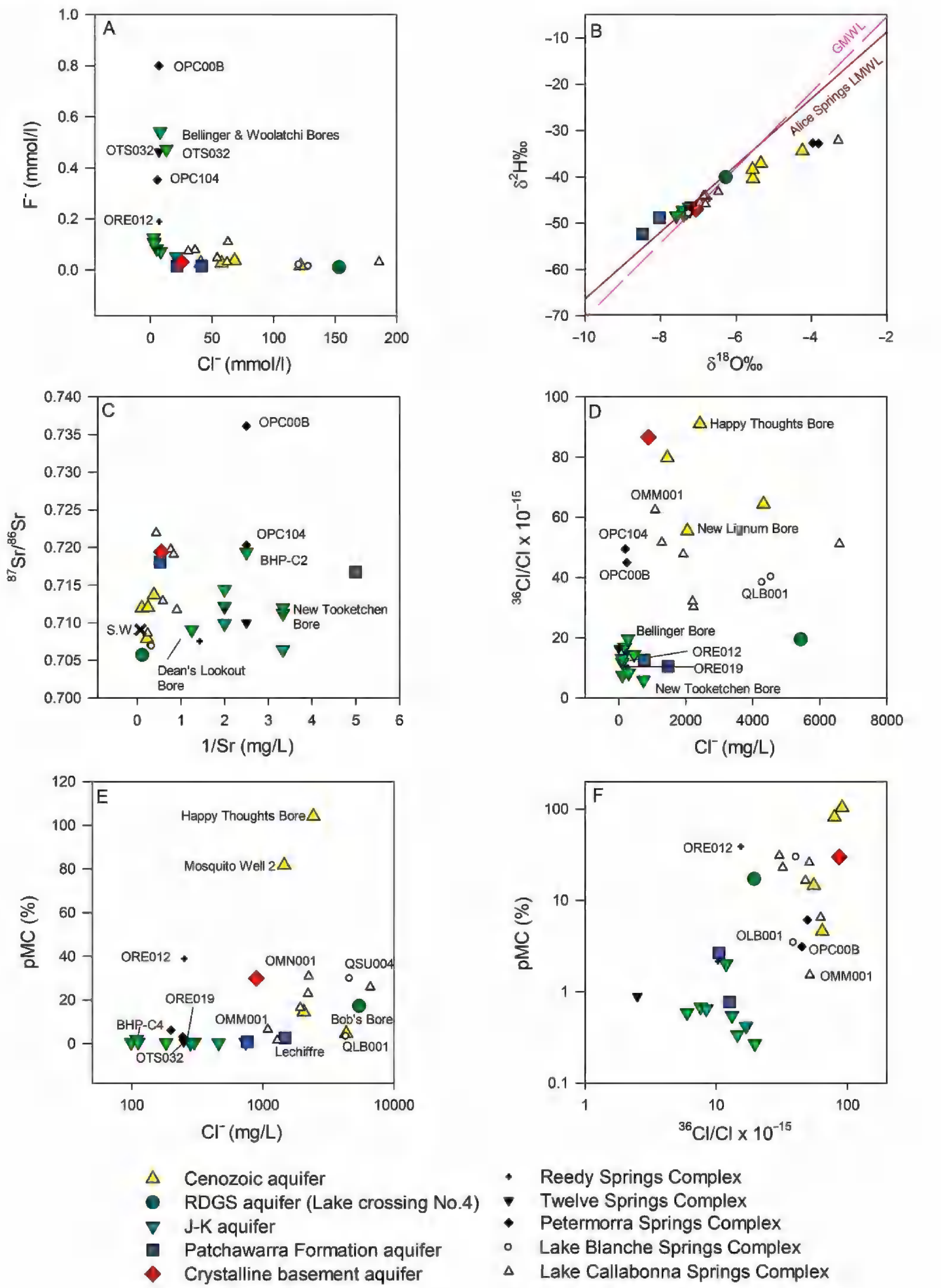


Table 4. Major ion and selected trace element results: (S) Data collected during this study; (H) istorical data.

Unit No.	Name	Data source	Aquifer	Cl (mg/L)	HCO_3 (mg/L)	SO_4 (mg/L)	Ca (mg/L)	K (mg/L)	Mg	Na (mg/L)	F (mg/L)	Br (mg/L)	Sr (mg/L)
673800024	Happy Thoughts	S	Cenozoic	2426	647	1941.1	399.0	3.0	201.0	1820	0.7	3.2	9.4
683800013	New Lignum Bore	S	Cenozoic	2049	236	864.3	198.0	7.0	133.0	1260	0.5	1.4	4.0
683800048	Mosquito Well 2	S	Cenozoic	1452	299	405.2	202.0	6.0	44.7	911	0.5	0.9	2.6
693900015	Bob's Bore	S	Cenozoic	4323	118	1886.4	259.0	20.1	118.0	3100	0.3	6.0	4.4
673900011	Warraninna Tank Bore	H	RDGS	4362	189	165.0	187.0	19.0	22.0	2780			
683800006	Lake Crossing Bore No. 4	S	RDGS	5432	107	1253.8	304.0	17.1	36.1	3380	0.2	3.7	8.5
683900003	Montecollina	S	RDGS/J-K	3616	192	89.8	125.0	14.1	20.2	2230	0.2	4.7	3.6
673800007	Quartpot	H	J-K	393	819	12.5	13.3	4.5	2.3	519			
673800189	BHP C4	S	J-K	109	886	0.4	11.5	14.1	1.1	386	2.1	0.2	0.5
673900002	Toonketchen Bore	H	J-K	146	992	1.0	5.0	6.0	0.4	445			
673900006	Meteor Bore	S	J-K	183	986	3.2	11.8	5.0	1.8	470	1.6	0.3	0.3
673900016	BHP C2	S	J-K	99	867	0.1	10.5	15.6	1.2	358	2.4	0.2	0.4
673900034	New Tooketchen	S	J-K	112	752	0.2	10.4	11.9	0.8	353	2.0	0.2	0.3
683800003	Dean's Lookout	S	J-K	741	532	0.2	22.1	8.6	3.3	621	1.0	0.6	0.8
683800004	Petermorra Bore	H	J-K	181	928	0.1	9.2	4.0	0.9	445			
683800022	Woolshed Bore	H	J-K	516	615	1.0	10.0	11.0	4.0	560			
683800029	Woolatchi	S	J-K	460	723	0.7	8.4	8.5	0.8	562	9.0	0.6	0.5
683800046	Bellinger Bore	S	J-K	280	741	0.0	11.4	5.1	1.6	448	10.3	0.4	0.5
693700006	Muloowurtina 2	H	J-K	315	1120	1.0	4.8	6.0	1.0	624			
693700013	WK 1	H	J-K	270	1149	4.3	7.9	9.7	1.7	582			
693700014	WK 2	H	J-K	259	1139	1.0	7.4	9.0	1.6	597			
693800001	Yandama Bore	H	J-K	295	1180	1.0	9.4	11.8	1.9	611			
703900005	Fortville 3	S	J-K	300	1038	0.3	11.4	22.0	2.0	620	1.4	1.0	0.3
683900058	Klebb-1	S	Patchawarra Formation	764	1387	10.1	40.5	71.8	6.6	1070	0.3	2.0	0.2
693900031	Lechiffre	S	Patchawarra Formation	1475	1135	6.4	71.4	71.6	7.7	1390	0.3	4.7	1.9
673800080	Bore A	H	Fractured rock basement	581	350	436.0	31.0	38.0	52.0	549			
673800080	Bore A	H	Fractured rock basement	606	366	438.0	28.0	37.0	51.0	582			

Unit No.	Name	Data source	Aquifer	Cl (mg/L)	HCO_3 (mg/L)	SO_4 (mg/L)	Ca (mg/L)	K (mg/L)	Mg	Na (mg/L)	F (mg/L)	Br (mg/L)	Sr (mg/L)
673800081	Bore B	H	Fractured rock basement	661	427	407.0	97.0	24.0	77.0	562			
673800081	Bore B	H	Fractured rock basement	599	444	357.0	87.0	24.0	67.0	513			
673800082	No. 2	H	Fractured rock basement	696	766	389.0	128.0	15.0	166.0	526			
683800037	Mt Fitton OS Bore	S	Fractured rock basement	891	555	719.0	100.0	7.6	133.0	666	0.6	2.3	1.8
673800009	Petermorra Mounds Spring	H	Spring	1705	645	812.0	115.0	12.0	56.0	1489			
673800063	Reedy Spring 19 (ORE019)	S	Spring	266	2511	12.0	16.0	15.0	5.0	1048	1.6	0.2	0.5
673800064	Reedy Spring 275 (ORE275)	H	Spring	12800	94	3569.0	1162.0	35.0	345.0	7775			
673800758	Reedy Spring 12 (ORE012)	S	Spring	251	1366	201.3	11.9	8.0	6.6	781	3.6	0.4	0.7
673801051	Reedy Spring 19 (ORE019)	H	Spring	145	871	3.2	16.6	14.5	4.3	402			
673900031	Sunday Spring 4 (QSU004)	S	Spring	4535	312	1218.6	179.0	26.6	95.5	3030	0.3	7.5	3.3
683800001	Public House Spring 104 (OPC104)	S	Spring	199	891	5.5	15.1	7.5	2.7	442	6.7	0.3	0.4
683800001	Public House Spring 104 (OPC104)	H	Spring	1670	7147	767.0	6.0	32.0	1.0	4033			
683800002	Chimney Spring 1 (OCH001)	H	Spring	281	858	13.0	11.0	6.0	3.0	473			
683800016	Mulligan Mid Spring 2 (OMM002)	S	Spring	1288	398	242.1	67.0	14.4	33.3	865	1.5	0.9	1.3
683800016	Mulligan Spring	H	Spring	1465	455	265.0	55.0	13.0	28.0	1112			
683800019	Twelve Springs	H	Spring	259	852	24.3	13.3	6.3	1.5	494			
683800019	Twelve Springs	H	Spring	1012	1087	21.0	27.0	6.0	11.0	1084			
683800020	Terrapinna Water	H	Spring	6209	253	3280.0	399.0	52.0	625.0	4069			
683800036	Mount Fitton Spring	H	Spring	759	449	360.0	94.0	12.0	161.0	418			
683800435	Public House Spring B (OPC000B)	S	Spring	245	853	65.7	11.9	6.6	2.4	497	15.2	0.3	0.4
683800705	Twelve Spring 32 (OTS032)	S	Spring	249	859	0.0	11.7	5.9	2.0	473	8.8	0.4	0.4
683800810	Mulligan Mid Spring 1 (OMM001)	S	Spring	1089	419	225.0	60.5	13.7	29.5	783	1.4	0.7	1.2
683800833	Mulligan North Spring 1 (OMN001)	S	Spring	2234	375	465.9	116.0	37.8	55.6	1460	2.1	1.5	2.3
683900049	Lake Blanche Spring 1 (QLB001)	S	Spring	4264	253	1176.2	165.0	20.0	88.8	2890	0.4	7.0	3.1
693800072	L.Callabonna South Spring 1 (ZCA001)	S	Spring	2206	513	329.3	48.1	17.8	26.2	1590	0.6	2.0	1.1
693800081	L.Callabonna East Spring 1 (ZCE001)	S	Spring	6584	192	1967.5	231.0	23.7	130.0	4170	0.6	6.1	4.2
693800117	L.Callabonna Mid Spring 1 (ZCM001)	S	Spring	1924	546	357.2	74.4	23.6	46.1	1380	0.9	1.4	1.7

Table 5. Stable isotope, $^{87}Sr/^{86}Sr$, radiocarbon and chlorine-36 results.

Name	Aquifer	$\delta^{18}O$ (‰)	$\delta\,^{2}H$ (‰)	$^{87}Sr/^{86}Sr$	2se	pMC (%)	pMC error	$^{36}Cl/Cl$ ($\times10^{-15}$)	$^{36}Cl/Cl$ ($\times10^{-15}$) error	^{36}Cl atoms/L $\times 10^{-7}$
Happy Thoughts	Cenozoic	–5.34	–37.1	0.71197954	0.000003	104.09	0.34	91.1	3.9	374.78
New Lignum Bore	Cenozoic	–5.55	–40.4	0.71202804	0.000003	14.5	0.21	55.5	2.9	192.82
Mosquito Well 2	Cenozoic	–5.56	–38.4	0.71370602	0.000003	81.69	0.29	79.8	3.8	196.47
Bob's Bore	Cenozoic	–4.24	–34.4	0.70790656	0.000003	4.59	0.12	64.4	2.9	472.12
Lake Crossing No.4	RDGS	–6.27	–40.09	0.70574066	0.000003	17.15	0.13	19.5	1.5	179.63
Montecollina	RDGS/J-K	–6.66	–43.1	0.70588773	0.000003	1.63	0.12	5.9	0.7	36.18
BHPB C4	J-K	–7.33	–47.5	0.71444982	0.000004	2.02	0.12	11.9	1.2	2.20
Meteor Bore	J-K	–7.22	–47.2	0.70643565	0.000003	0.42	0.12	16.9	1.3	5.25
BHPB C2	J-K	–7.39	–48.1	0.71939384	0.000004	0.55	0.12	13.2	1.6	2.22
New Toonketchen	J-K	–7.31	–47.6	0.71126888	0.000003	0.68	0.12	7.6	0.9	1.44
Dean's Lookout	J-K	–7.17	–46.2	0.70909665	0.000003	0.59	0.15	6.0	0.8	7.54
Woolatchi	J-K	–7.41	–47.2	0.71219994	0.000003	0.34	0.22	14.5	1.1	11.32
Fortville 3	J-K	–7.58	–48.4	0.71201216	0.000003	0.65	0.12	8.4	0.9	4.28
Bellinger Bore	J-K	–7.24	–46.5	0.70991779	0.000003	0.27	0.22	19.7	1.2	9.33
Klebb-1	Patchawarra Formation	–8.03	–48.8	0.71673837	0.000006	0.77	0.12	12.6	1.1	16.33
LeChiffre-1	Patchawarra Formation	–8.48	–52.3	0.71806382	0.000003	2.65	0.12	10.5	1.0	26.27
Mt Fitton OS Bore	Fractured rock basement	–7.06	–47.0	0.71942160	0.000003	29.94	0.21	86.6	4.0	130.77
Twelve Spring 32 (OTS032)	Spring	–7.26	–46.8	0.71001391	0.000003	0.89	0.22	16.6	0.9	7.01
Mulligan Mid Spring 1 (OMM001)	Spring	–6.81	–45.9	0.71910540	0.000003	6.49	0.22	62.5	3.2	115.35

Name	Aquifer	$\delta^{18}O$ (‰)	$\delta\,^2H$ (‰)	$^{87}Sr/^{86}Sr$	2se	pMC (%)	pMC error	$^{36}Cl/Cl$ ($\times10^{-15}$)	$^{36}Cl/Cl$ ($\times10^{-15}$) error	^{36}Cl atoms/L $\times 10^{-7}$
Mulligan Mid Spring 2 (OMM002)	Spring	–6.96	–45.6	0.71975430	0.000003	1.52	0.22	51.7	2.7	112.95
Mulligan North Spring 1 (OMN001)	Spring	–6.47	–43.2	0.72195187	0.000003	30.92	0.21	30.3	2.4	114.73
L. Callabonna South Spring 1 (ZCM001)	Spring	–6.81	–44.0	0.71174507	0.000003	16.48	0.18	32.1	1.7	571.38
L. Callabonna Mid Spring 1 (ZCA001)	Spring	-6.86	–44.1	0.71291711	0.000003	25.97	0.18	47.8	2.9	156.08
L. Callabonna East Spring 1 (ZCE001)	Spring	–3.29	–32.1	0.70864585	0.000003	22.93	0.18	51.2	2.9	119.90
Lake Blanche Spring 1 (QLB001)	Spring	–3.96	–32.7	0.70694515	0.000003	3.47	0.12	38.5	2.2	278.40
Reedy Spring 12 (ORE012)	Spring	–6.71	–44.7	0.70755946	0.000003	38.88	0.17	15.4	1.2	6.57
Reedy Spring 19 (ORE019)	Spring	–7.16	–47.3	0.71182757	0.000003	2.15	0.12	10.3	0.9	2.54
Sunday Spring 4 (QSU004)	Spring	–3.81	–32.8	0.70703463	0.000003	30.01	0.16	40.4	2.1	310.67
Public House Spring B (OPC000B)	Spring	–7.26	–47.8	0.73612925	0.000003	3.11	0.15	45.0	2.3	18.72
Public House Spring 104 (OPC104)	Spring	–6.86	–45.7	0.72031497	0.000003	6.12	0.15	49.5	2.5	16.67

Although the results for the stable isotopes of water for the Cenozoic aquifer and shallow fractured rock basement aquifer are both likely to represent localised and recent groundwater recharge, the difference observed between the two suggests that recharge to the fractured rock basement aquifer occurs preferentially through a fracture system and therefore has less time to become enriched via evaporation. Furthermore, the depleted nature of results from the J-K aquifer and Patchawarra Formation compared to other aquifers is indicative of recharge either via different recharge mechanisms or under a different climatic regime.

Isotopic Strontium Ratios ($^{87}Sr/^{86}Sr$)

Results for isotopic strontium ratio ($^{87}Sr/^{86}Sr$) analysis are provided in Table 5. $^{87}Sr/^{86}Sr$ from the fractured rock basement aquifer and Patchawarra Formation are greater than 0.716, making them the highest on average when compared with other groundwater types (Figure 6C).

The J-K aquifer is generally lower than the Patchawarra Formation and fractured rock basement aquifer, with all but one of the $^{87}Sr/^{86}Sr$ ratios between 0.706 and 0.715, the exception being from well BHP-C2, which had a ratio of 0.7194 (Table 5). Importantly, the J-K aquifer Sr^{2+} concentration generally falls within a narrow range compared to other groundwater types, varying between 0.285 mg/L and 0.81 mg/L. However, when strontium concentrations are presented as a reciprocal (1/Sr), the results between 1.3 (Dean's Lookout) and 3.3 (New Toonketchen) are indicative of strontium loss via calcite precipitation. This subtle change in concentration is also indicated when the Ca^{2+}/Cl^- ratio is compared to Cl^- (Figure 4E), where an inversely proportional relationship is noted in the J-K aquifer. As Sr^{2+} has similar physical and chemical properties to calcium, these relationships suggest Sr^{2+} and Ca^{2+} loss via mineral precipitation with increasing salinity.

$^{87}Sr/^{86}Sr$ ratios from the RDGS aquifer are low (<0.706) compared to samples from the J-K aquifer (Table 5), Cenozoic aquifer and Patchawarra Formation, and are slightly lower or similar to the modern seawater $^{87}Sr/^{86}Sr$ ratio (Figure 6C). Additionally, Sr^{2+} concentrations ranging between 3.6 and 8.5 mg/L are generally higher in the RDGS aquifer compared to the J-K aquifer, Patchawarra Formation and fractured rock basement aquifer; although similar in concentration to the Cenozoic aquifer (Table 5).

Radioisotopes: Radiocarbon and $^{36}Cl/Cl^-$

Radioisotope results are provided in Table 5. Only one sample (Mt Fitton OS Bore) represents the radiocarbon and $^{36}Cl/Cl^-$ signatures from the fractured rock basement aquifer. Therefore, interpretations based on these results are limited. Mt Fitton OS Bore has a $^{36}Cl/Cl^-$ ratio of 86.6×10^{-15} and radiocarbon concentration of 30 pMC (Table 5) which are elevated compared to groundwater from the J-K aquifer and Patchawarra Formation (Figure 6D; Figure 6E). The shallow total depth of the bore (37 m) and depth to groundwater (4.32 m) suggest that groundwater collected from this well is part of a localised flow path within the crystalline basement fractured rock aquifer. Although we have not corrected pMC results to derive an apparent age as there is insufficient context to interpret a groundwater flow vector to an acceptable level of certainty to interpret recharge and discharge zone localities, previous work examining radiocarbon in the South Australian portion of the GAB (Wohling et al., 2013) suggests that the presence of modern carbon in groundwater is strongly indicative of relatively more recent recharge when compared with results derived from the regionally extensive J-K aquifer within the general vicinity of the study area.

The uncorrected radiocarbon and $^{36}Cl/Cl^-$ ratio results from the Patchawarra Formation and J-K aquifer indicate older groundwater compared to most other groundwater types (Figure 6D; Figure 6E; Table 5). All but two results have uncorrected radiocarbon of <1 pMC, with the exceptions (BHP-C4 and Lechiffre) still considered to show very old groundwater (2.02 pMC and 2.65 pMC, respectively) (Table 5). Likewise, $^{36}Cl/Cl^-$ ratios of between 7.6×10^{-15} (New Toonketchen Bore) and 19.7×10^{-15} (Bellinger Bore) are considered to represent old groundwater. These results support the assertion obtained from major ion, stable isotopes of water and $^{87}Sr/^{86}Sr$ results that the groundwater type from these two aquifers is similar, albeit based on a limited sample size.

The radiocarbon and $^{36}Cl/Cl^-$ ratios from the RDGS aquifer are represented by one well (Lake

Crossing No. 4), and therefore interpretations based on these results are limited. The radiocarbon and $^{36}Cl/Cl^{-}$ ratios are 17.2 pMC and 19.5 × 10^{-15} $^{36}Cl/Cl^{-}$, respectively (Table 5). These results are not directly comparable with the range of uncorrected apparent groundwater ages from other aquifers.

Groundwater in the Cenozoic aquifer exhibits a wide age distribution as defined by the uncorrected radiocarbon and $^{36}Cl/Cl^{-}$ results (Figure 6D; Figure 6E). Results for $^{36}Cl/Cl^{-}$ varied between 55.5 × 10^{-15} (New Lignum) and 91.1 × 10^{-15} (Happy Thoughts), and radiocarbon varied between 4.6 pMC (Bob's Bore) and 104.1 pMC (Happy Thoughts) (Table 5). This may reflect the occurrence of a number of localised groundwater recharge zones to the Cenozoic aquifer across the investigation area. We note that Mosquito Well 2 and Happy Thoughts, which provided groundwater with the youngest apparent ages, are located close to ephemeral creeks, suggesting that the surface drainage across the investigation area may be providing at least one potential source of recharge to the Cenozoic aquifers.

Hydrochemistry of Springs

When analysed in comparison to the well data, the spring data suggest that many springs within the study area are likely to have multiple or mixed aquifer sources; it appears that only some of the springs can be linked to a single aquifer source.

The hydrochemistry of spring water samples from the Twelve Spring complex compares conclusively with the J-K aquifer, whereas the Reedy and Petermorra Springs complex display a predominant contribution from the J-K aquifer. The major ion concentrations of these spring waters can be described as $Na^{+} + HCO_3^{-} + (Cl^{-})$ and are therefore similar to the J-K aquifer (Figure 3). Elevated F^{-} in spring water samples from Public House Springs in the Petermorra Springs complex (OPC000B and OPC104), Twelve Springs 32 (OTS032) and Reedy Springs 12 (ORE012) is most likely related to a primary source of water, being the J-K aquifer (Figure 6A; Table 4).

In contrast, the hydrochemistry of spring water from the Lake Blanche Springs complex, Reedy Springs 275 (ORE0275), Petermorra Mound Spring and Mt Fitton Spring (Petermorra Springs complex), Terrapinna Waters Spring and the Lake Callabonna Springs complex indicates that an aquifer other than the J-K aquifer is the primary source. In the case of Mt Fitton Spring and Petermorra Mound Spring in the Petermorra Springs complex, $Na^{+} + (Ca^{2+} + Mg^{2+}) + Cl^{-} + SO_4^{2-}$ dominant water type is most closely comparable to the fractured rock basement aquifer (Figure 3). Given the location of these springs at the margin of the GAB and near the Northern Flinders Ranges, a fractured rock crystalline basement aquifer source seems plausible. Further, the very high $^{87}Sr/^{86}Sr$ ratios from Public House Springs B (OPC00B) within the Petermorra Springs complex is most comparable to results from crystalline basement fractured rock aquifer groundwater and therefore suggestive of a non-J-K aquifer source as well (Figure 6C).

The proportional major ion concentrations for the Lake Callabonna Springs complex, Reedy Springs 275 (ORE0275) and Terrapinna Waters are comparable to Mt Fitton Spring and Petermorra Mound Spring (Figure 3). Despite this similarity, the thickness of basinal sedimentary rocks is approximately 1000 m at these locations; the source aquifer could potentially be either the Cenozoic aquifer, the RDGS aquifer or possibly the J-K aquifer. However, there is currently no evidence to suggest that the Cenozoic aquifer is artesian in this region, and therefore it is unlikely to be a primary source aquifer for springs. In contrast, artesian conditions are known to occur within Neocretaceous aquifers, including the RDGS aquifer.

Radiocarbon and $^{36}Cl/Cl^{-}$ results were found to be important for discriminating between J-K aquifer and non-J-K aquifer sources. Many samples from the aforementioned springs contain elevated radiocarbon and $^{36}Cl/Cl^{-}$ ratios, which strongly contrast with results from the J-K aquifer, which are typically very low. $^{36}Cl/Cl^{-}$ ratios from springs were consistently elevated, with ratios greater than 30 × 10^{-15} obtained from the Lake Callabonna Springs complex, Lake Blanche Springs complex and Petermorra Springs complex. Exceptions to this include Twelve Springs, Reedy Springs 12 (ORE012) and Reedy Springs 19 (ORE019) ($^{36}Cl/Cl^{-}$ <17 × 10^{-15}) (Figure 6D; Table 5). Radiocarbon results from springs in the Lake Callabonna Springs complex, Reedy Spring 12 (ORE012) and Sunday Springs 4 (QSU004, Lake Blanche complex) are greater than 20 pMC (Table 5). Exceptions to this include Twelve Springs 32 (OTS032), Mulligan

Mid Springs 1 (OMM001, Lake Callabonna complex), Lake Blanche Spring 1 (QLB001), Reedy Springs 19 (ORE019) and Public House Springs group (Petermorra Springs complex), which all had radiocarbon <7 pMC (Figure 6E; Table 5).

A comparison of radiocarbon and $^{36}Cl/Cl^-$ ratios displays a broad correlation, suggesting that the overall trends in uncorrected apparent groundwater age between the aquifer types as described above are reliable (Figure 6F). However, important differences in uncorrected apparent groundwater age using radiocarbon and $^{36}Cl/Cl^-$ ratios were found from Public House Springs B (OPC00B) in the Petermorra Springs complex, Reedy Spring 12 (ORE012), Mulligan Springs Mid 1 (OMM001) and Lake Blanche Spring 1 (QLB001) (Table 5; Figure 6D; Figure 6E; Figure 6F). In the case of Public House Springs B (OPC00B), Mulligan Springs Mid 1 (OMM001) and Lake Blanche Spring 1 (QLB001), $^{36}Cl/Cl^-$ ratios suggest a younger groundwater age compared to the J-K aquifer, whereas radiocarbon suggests a reasonable comparison to the J-K aquifer. The opposite is true of the Reedy Springs 12 (ORE012) dataset, which suggests a younger groundwater age compared to the J-K aquifer, and reasonable comparison using the $^{36}Cl/Cl^-$ ratios in isolation. These differences may have one of a number of causes, including:

- The source of water to these particular springs may be from several aquifers.
- Suckow et al. (2020) recently suggested that double porosity within an aquifer, and the different diffusion rates from the tighter pore space component this may impart to radioisotopes within the same groundwater, may be used to explain different apparent groundwater ages from multiple tracers.
- Sample contamination can also not be ruled out.

Discussion

Major Ion and F-hydrochemistry of the J-K Aquifer

$Na^+ + HCO_3^- + (Cl^-)$ dominant groundwater from the J-K aquifer was described by Habermehl (1980), Herczeg et al. (1991) and Priestley et al. (2013) as being predominantly sourced from the eastern portion of the GAB. In contrast, the J-K aquifer along the western margin of the GAB is predominantly $Na^+ + Cl^- + SO_4^{2+}$ (Priestley et al., 2013). Herczeg et al. (1991) used mass-balance and equilibrium hydrochemistry models to describe the likely water–rock interactions responsible for the predominance of $Na^+ + HCO_3^-$ hydrochemistry in J-K aquifer groundwater: (a) dissolution of Na-bearing minerals (e.g. plagioclase and orthoclase); (b) cation exchange that releases Na^+ for Ca^{2+}–Mg^{2+}; and (c) conversion of Na-smectite to kaolinite. In particular, the incongruent dissolution of albite will release both Na^+ and HCO_3^- at a ratio of 1:1, which is the same ratio displayed from J-K aquifer groundwater in Figure 5E and Figure 5F.

Edmunds and Smedley (2013) indicate that F^- is more stable in solution if Ca^{2+} is low, because of the relative insolubility of fluorite (CaF_2) and the affinity of Ca^{2+} to react with F^- at temperatures typically found in groundwater. Therefore, in keeping with the findings of Herczeg et al. (1991), ion exchange or mineral precipitation that results in at least the partial removal of Ca^{2+} from solution might be responsible for relatively elevated F^- in J-K aquifer groundwater.

Rolling Downs Group Sandstone Aquifer

A major finding of this study was the identification of artesian groundwater from a relatively shallow Cretaceous sandstone aquifer found within the confining layer sequences of the Rolling Downs Group (Table 1; Figure 2), and that this RDGS aquifer is potentially a source aquifer for the Lake Blanche and Lake Callabonna Spring complexes. An analysis of hydrochemistry indicates that there are two artesian aquifers within the Great Artesian Basin (GAB) at this location (Figure 2). The deepest is the J-K aquifer, whereas the second is a shallower, thin (up to 37 m) sand unit that Keppel et al. (2016) and Sheard & Cockshell (1992) suggested may be the Coorikiana Sandstone (Table 1). However, recent work by Alley & Hore (2017) suggests that this unit may be the newly named Bellinger Sandstone (Table 1).

A small number of historical groundwater samples, as well as samples from Lake Crossing No. 4 collected during this study, are notably different from samples from wells completed within the J-K aquifer. Wells from which these samples were collected were determined to be completed in

the RDGS aquifer based upon a review of lithological logging and comparison with logging from nearby wells (Keppel et al., 2016). Furthermore, although Montecollina Bore is ostensibly completed within the J-K aquifer, both historical and current hydrochemistry results suggest an RDGS aquifer source. Additionally, monitoring and bore repair records indicate that not only was significant groundwater encountered within this shallow sandstone unit, but it was highly likely that the aquifer leaked groundwater into this well. This is evidenced by its history of corrosion, maintenance issues and structural condition before decommissioning in 2019, as well as complementary historical salinity records (Keppel et al., 2016).

Hydrochemistry of Springs and Relationship to Groundwater Types

Although the majority of spring water samples can be compared favourably to the J-K aquifer, a number of spring waters indicate other groundwater types as the primary source. Springs within the investigation area may åbe divided into two broad collections based on hydrochemistry. The first collection, which primarily comprises Twelve, Reedy and Petermorra Springs complexes, are most comparable to the J-K aquifer. The second collection, which primarily comprises the Lake Callabonna and Lake Blanche Spring complexes, is not consistent with the J-K aquifer being the sole source aquifer, but rather, significant groundwater contributions are very likely from other aquifers. Further, within the first collection, individual spring vents at both the Petermorra and Reedy Spring complexes suggest a minor contribution from other aquifers. A summary of likely groundwater sources for the various spring complexes is provided in Table 6.

Although the hydrochemical differences between the J-K aquifer and the Patchawarra Formation are small, no spring system could be definitively linked to the Patchawarra Formation using hydrochemistry when the location of the springs was compared to the extent of the Cooper Basin. Youngs (1971) and Altmann & Gordon (2004) noted that groundwater from the J-K aquifer and Cooper Basin strata can intermix if confining layers between the two aquifers have been removed via erosion before the deposition of GAB (Eromanga Basin) sedimentary sequences. That being said, springs that have the most similar hydrochemical profile to groundwater from the Patchawarra Formation include Twelve Springs and Petermorra Springs, which are located approximately 40 km south of the southern margin of the Cooper Basin and are therefore supplied by the J-K aquifer.

Table 6. Summary of possible sources of spring water based on hydrochemistry.

Spring complex	Possible supplying aquifer
Lake Blanche	RDGS aquifer/Cenozoic
Reedy	J-K aquifer (and RDGS/Cenozoic)
Petermorra	J-K aquifer (and crystalline basement fractured rock aquifer)
Twelve	J-K aquifer
Lake Callabonna (Mulligan Group)	Cenozoic, RDGS aquifer and J-K aquifer (?) (mix)
Lake Callabonna (Callabonna Group)	Cenozoic, RDGS aquifer and J-K aquifer (?) (mix)

Implications for Management

The identification of the RDGS aquifer in the region has important ramifications for understanding the hydrogeology of the GAB south of the Cooper Basin. The discovery of a second distinct artesian aquifer within the Mesozoic strata of the GAB raises technical and management considerations related to their potential environmental and economic significance. Although reasonably salty in the well sampled (Table 2), the RDGS aquifer is likely to have economic significance as a number of artesian pastoral bores are screened within it, with at least one (Lake Crossing No. 4) in apparent active use. At the forefront of these technical and management considerations are those concerning the origin, volume and hydrodynamics of groundwater

within the RDGS aquifer and the interconnectivity with the underlying J-K aquifer. Given the previous misidentification, there are also implications for previous interpretations and understanding of the hydrodynamics of the J-K aquifer. Finally, given the prevalence of ecologically sensitive spring environments, as well as established pastoral and petroleum industries in the region, management and regulation of groundwater affecting development requires a refocus from predominantly a single aquifer to potentially multiple aquifers.

It should be noted that although the work presented here has been able to identify the potential primary source aquifer for springs, further work is necessary to quantify both the environmental importance and the economic significance of these resources. For instance, hydrochemical modelling, such as a mixing model, is a necessary next step to identify the potential for, and to quantify, mixing between different groundwater sources. Ideally, nested piezometers designed to assess the hydraulics and connectivity of multiple aquifers are required. Nevertheless, this study demonstrates that a regional-scale hydrochemistry survey using a variety of analytes is a simple and valuable first step towards understanding the relationship between springs and source aquifers, and highlighting potential management issues.

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Oases at the Gates of Hell: Hydrogeology, Cultural History and Ecology of the Mulligan River Springs, Far Western Queensland

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Abstract

The Mulligan River springs occur on the eastern edge of the Simpson Desert in far south-west Queensland, near the north-west margin of the Great Artesian Basin, and are associated with the Toomba Thrust Fault. The springs provide the only permanent surface water in the driest part of Australia. They have been focal points for human and animal activity for millennia, but despite their cultural and ecological interest, they have received relatively little attention compared to other Great Artesian Basin spring groups. Here we explore the hydrogeology, cultural history and ecology of these springs through a review of published literature, early explorer journals, diaries and letters of early settlers, books, and comprehensive field survey. Fragments of stories and dense surface archaeology indicate intensive occupation at many of the springs by the Wangkamadla people for thousands of years, but most of the knowledge about how people used, mythologised and managed the springs did not survive the frontier period that saw the area depopulated. From the 1880s, explorers and pastoralists marvelled at, relied upon and in many cases severely modified the springs. Shallow bores were sunk on or near springs, and others were excavated to improve cattle access. Today, all except three of 90 documented springs remain active, although many are highly modified and reductions in flow and wetland extent due to aquifer drawdown are likely to have occurred. No endemic species are known to be associated with the Mulligan River springs, but they support disjunct populations of some plants and fish. There appears to be considerable natural dynamism in spring activity and flow, but springs in some areas have emerged or become reactivated, apparently due to increased aquifer pressure following bore capping. Additional springs were found during the most recent surveys, and a small number probably remain undocumented. Improved understanding of recharge areas, aquifer connectivity and spring dynamism will inform future management of these isolated oases, while detailed archaeological work will shed light on patterns of Aboriginal use and better situate the springs in the wider cultural landscape.

Keywords: hydrogeology, cultural history, ecology, wetland extent, aquifer drawdown, grazing disturbance

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Introduction

Ascending one of the sand ridges I saw a numberless succession of these terrific objects rising above each other to the east and west of me … I find it utterly impossible to describe the appearance of the country … The scene was awfully fearful: a kind of dread came over me as I gazed upon it. It looked like the entrance into Hell (Captain Charles Sturt, 7 September 1845).

When a scurvy-ravaged Captain Charles Sturt, finally thwarted in his attempt to reach the geographic centre of the continent, described the eastern edge of what is now known as the Simpson Desert in a letter to his wife Charlotte, the country to the west was completely unknown to white Australians. He could not have known that even here, in the driest part of Australia, his red sandy hell, lay ancient wells (*mikiri*) and spring-fed pools that had sustained desert people for millennia.

It was another four decades before descriptions of the springs that form the Mulligan River supergroup were published. Mulligan River Springs is one of 12 spring 'supergroups' emanating from the Great Artesian Basin (GAB), a series of interconnected sandstone aquifers underlying one-fifth of Australia (Habermehl, 2006). Water enters the GAB mostly at its eastern margin along the Great Dividing Range, and percolates through the sandstone in a generally south-westerly direction. Springs are natural discharge points for this water, and occur around the basin's edges or along fault lines in western Queensland, north-west New South Wales and north-east South Australia. The journey from the intake beds to the desert springs may take millions of years (Habermehl, 2001).

The Mulligan River supergroup occurs along the north-eastern margins of the Simpson Desert in far south-western Queensland (Figure 1). The climate is hot and arid, with summer daytime maximum temperatures regularly exceeding 40°C, and an average annual rainfall of 165 mm at the geographic centre of the supergroup (derived from the modelled surface in SILO; Jeffrey et al., 2001). Rainfall is characterised by high inter-annual variability, while the study area is also subject to flooding from intermittent tropical monsoons to the north. This supergroup has received comparatively little attention from researchers, compared to the considerable interest in springs in other areas of Queensland (Fairfax & Fensham, 2003; Kerezsy & Fensham, 2013; Rossini et al., 2017), and in New South Wales (Pickard, 1992; Powell et al., 2015) and South Australia (Harris, 1981; Harris, 2002). They were not included in recent research investigating hydrogeological, ecological and cultural knowledge of numerous spring groups (Silcock et al., 2014; Fensham et al., 2016).

Here we explore the hydrogeology, cultural history and ecology of the Mulligan River springs. Locations of springs were documented by combining the results of a previous survey (Fensham & Fairfax, 2003) with examination of historical maps (survey run plans and the Queensland '4 mile' series) and Google Earth imagery; a review of journals, diaries, letters and newspaper articles by early explorers, pastoralists and travellers; and interviews with contemporary pastoral station managers. All known and potential spring sites were visited between May and August 2013. At each spring, the landscape position and surrounding vegetation were described and photos taken. Each vent in a spring group was marked with a hand-held GPS and its activity status recorded. For active springs, soak and wetland area (defined as >50% cover of wetland vegetation), excavation damage (wells, pipes, bores, direct excavation) and impacts of stock and feral animals were recorded. All plant species present in the spring wetland were recorded, and the wetland was surveyed for fish, molluscs and other invertebrates. Where there was free water, water chemistry measurements (temperature, pH and conductivity) were taken. We also noted surface archaeology at and around springs, and supplemented these observations with ethnographic observations from explorer and early settler journals and diaries, monographs and books, as well as contemporary ethnographic and archaeological studies. Camera traps were set up on nine springs between August 2012 and May 2013 to document fauna use.

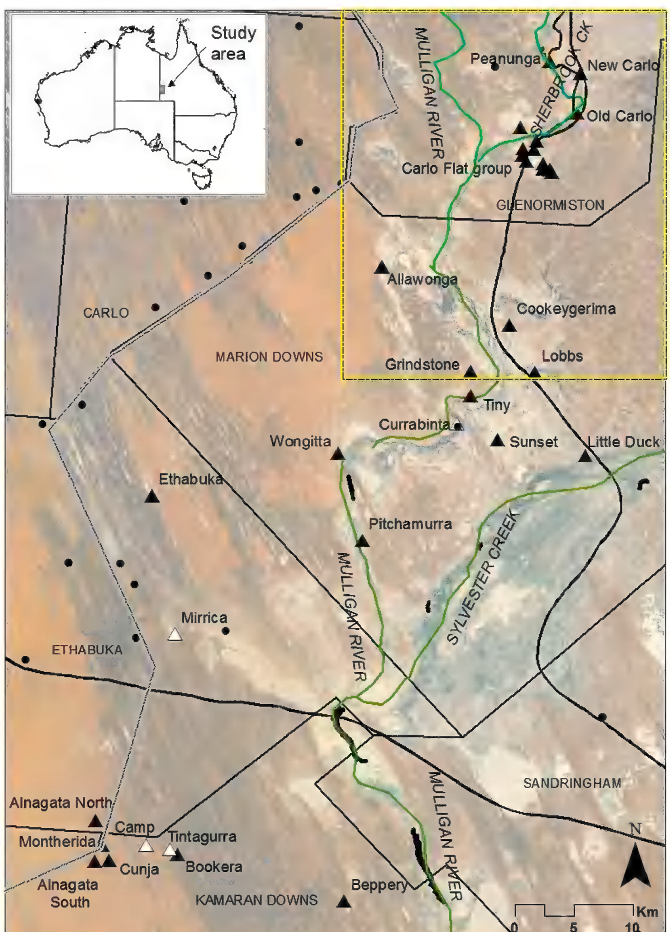
Hydrogeology

The Mulligan River springs occur near the north-western margin of the GAB, and the source aquifer is the Hooray Sandstone (Habermehl, 1982), formerly referred to as the Longsight Sandstone, with the Wallumbilla Formation acting as the overlying aquitard. The springs are associated with the Toomba Fault that has upthrown the sediments of the aquifer by up to 300 metres from the west (Simpson et al., 1985). The main Toomba Fault is 200 km long, has a vertical displacement of up to 6.5 km and contains 'fracture zones' measurable in square kilometres (Harrison, 1980). The fault provides a significant obstruction to groundwater flow and causes upwelling and discharge through the springs. It is aligned in a north–north-west direction between Beppery and Ethabuka Springs, and the

westerly line to Montherida Spring and north–north-easterly line to Peanunga Spring (Figure 1) may be associated with cross-faulting from the main fault.

The upwelling of groundwater at the Mulligan River springs coincides with an area where groundwater flow converges from all directions including the northern margin of the basin, which probably provides some local recharge (Radke et al., 2000). The spring water is relatively alkaline with high concentrations of total dissolved solids (Fensham & Fairfax, 2003). A more detailed analysis to determine the hydrogeology and contribution of groundwater recharged from the northern margin of the GAB is required for the Mulligan River springs.

Figure 1. The Mulligan River supergroup with main spring groups named. Active spring groups shown by black triangles; inactive spring groups, white triangles (the status of Camp Spring is unknown). Carlo Flat group includes Post, East, Crater, Brolga, Blacks, Natural Well, Talaera, Wandera, Triple and Eagle Springs. Major drainage lines are marked in green, and semi-permanent (containing water for >70% of the time on average) waterholes in black; bores are marked as black circles. Property boundaries are black; the now-abandoned rabbit-proof netting fence is shown in grey. The extent of the area shown in Figure 3 is marked by the yellow box. SPOT10 imagery as background shows the eastern margin of the Simpson Desert dunefields and floodplains of the Mulligan River and Sylvester Creek.



History of Aboriginal Occupation

The Wangkamadla people lived in the area encompassing the Mulligan River springs for millennia. The oldest recorded sites in the Simpson Desert date occupation to late Holocene (the last 3000 years; Smith, 2013), but landforms of the region are not ideal for deep-time archaeological sequences and sites to the north and south-east suggest earlier occupation of at least 10,000 years ago (Davidson, 1983; Robins, 1993). The presence of waterholes and springs along the Mulligan River suggest that it would have provided a 'corridor' for settlement and occupation, rather than a 'barrier' as typically hypothesised for Australia's dunefield deserts (Veth, 1993; Simmons, 2007; Smith, 2013). The springs provide the only permanent surface water in the area (Silcock, 2009), and were thus vital for human occupation, as well as supporting relatively high densities of game animals (Barton, 2001). People would have congregated around the springs during dry times and moved into other environments when ephemeral surface water allowed (Birdsell, 1971; Barton, 2001; Petersen, 2005).

Surface archaeology indicates intensive habitation and activity at many springs. Stone flakes and cores were found at 26 of the 33 major spring groups, and grindstones and hearths at 13 and four spring groups, respectively. There are large bone middens at three springs: Allawonga, Ethabuka and Bookera, all of which are situated in or near dunes. These middens and stone artefact scatters extend >1 km from the springs, and some middens contain the bones of now-extinct, medium-sized mammals. Archaeological assemblages at the springs reflect the length and intensity of site occupation, and use of the springs as residential base camps where a wide range of activities were undertaken (Barton, 2001). In Barton's (2001) study, two spring sites (Alnagata and Ethabuka) had the highest density and diversity of artefacts recorded across seven landscape units sampled. The quantity of grindstone material suggests large-scale processing of seeds during periods of site use by large numbers of people (Barton, 2001). Large ceremonial and social events were held near GAB springs around Lake Eyre (Horn & Aiston, 1924), and it is possible that similar gatherings were held at the Mulligan River springs. These springs lie on the western edge of an extensive trade system (McBryde, 2000), and provide the closest reliable water to extensive groves of the pituri shrub (*Duboisia hopwoodii*) that was harvested and traded throughout inland eastern Australia; dried pituri leaves and stems mixed with *Acacia* ash were chewed as a narcotic and an analgesic (Silcock et al., 2012). The role of the springs in this trade network has not been investigated, but they may have been stop-over points on these journeys, and possible sites for processing and preparation of pituri (Silcock et al., 2012).

Aboriginal belief systems have parallels with groundwater and spring mythologies worldwide, including the presence of ancestral beings and the healing power of the waters (Ah Chee, 2002; McDonald et al., 2005; Toussaint et al., 2005). There are a number of known stories following, traversing and associated with the Mulligan River (e.g. Hercus, 2013, 2014), and it is likely each of the springs would have been inscribed in story as part of the wider cultural landscape (Rose, 2004). The manipulation and management of water resources in Aboriginal Australia is well documented, and in relation to springs included regular cleaning to maintain depth and water quality, protection from animals, care and respect in use, and ceremonial elements (Stuart, 1865; Duncan-Kemp, 1934; Bandler, 1995; Bayly, 1999).

Early white explorers and travellers provide glimpses into Wangkamadla occupation and use of springs, although these observations were often cursory and made when Aboriginal society was already subject to the pressures that ultimately saw the area depopulated. In 1883, four decades after Charles Sturt's journey, surveyor-explorer Charles Winnecke provided the first written descriptions of the Mulligan River springs (Winnecke, 1884). His descriptions make it clear that he was entering a well-peopled country, within which the springs were focal points for survival and travel. He recorded the Aboriginal names for the springs he visited – Biparee, Boolcoora, Tintagurra, Montherida, Alnagatar, Cunja and Etabucka – from his Aboriginal guide, Blucher. When he visited, there were people camped at Biparee and the springs north-west of Tintagurra, and Winnecke found four axes and a tomahawk buried at Ethabuka Spring. These evocative spring names – and others including Mirrica, Allawonga, Wongitta, Currabinta, Peanunga, Talaera, Wandera, Pitchamurra and Cookeygermina – survive the

colonial period that saw the area depopulated, but the stories behind these names were not recorded.

In 1885, government surveyor Twisden Bedford recounted a story from the Mulligan River of an "oracle" who lived at the bottom of a spring, possibly the Ethabuka Spring, which was thought to be bottomless (Winnecke, 1884). This oracle, "big fellow masser", was consulted in a strange manner:

> … one Aboriginal taking a big stone in each hand, dived head first into the bubbling water. A second Aboriginal jumped in immediately afterwards, and catching hold of his predecessor's legs, which appeared above the surface of the water, forced him further down. A third Aboriginal then jumped in and forced the second down, all remaining under the water for as long a time as they could hold their breath in abeyance. They then all came to the surface, when the leading native gravely announced that he had interviewed the big fellow masser, and that big fellow flood come up along a one-fellow moon. And what is more, the flood did come in another month as predicted (Bedford, 1886, p. 112).

From the 1870s, the pastoral frontier rapidly enveloped Wangkamadla country. Across the Channel Country and Simpson Desert, massacres, disease and addiction decimated the lives of Aboriginal people (Roth, 1897; Watson, 1998). Permanent water points were often sites of frontier conflict in arid Australia, although such incidents were poorly documented and often deliberately concealed (Watson, 1998; Jackson & Barber, 2016). No massacres are documented from Wangkamadla country, but there were Native Police stationed across the region and violence in surrounding areas (Lamond, 1953; Hercus & Sutton, 1986; Bottoms, 2013). It is likely that any Wangkamadla people still living on country moved into towns and stations during the severe drought of 1899–1900, as has been documented for the Wangkangurru people, the Wangkamadla's southern neighbours (Hercus, 1985). Some Wangkamadla people worked on pastoral stations in the area, including Glenormiston, Sandringham and Marion Downs, and others continue to reside in the towns of Bedourie, Urandangi, Boulia and Mt Isa (Kelly, 1968; Davidson, 1983; Barton, 2001). All current property managers we spoke with recognise the significance of the country encompassing the springs to the Wangkamadla, and people continue to visit sites in the area.

Colonial Exploration and Pastoral History

As the pioneer prospectors and pastoralists pushed to the edges of the desert country in the 1880s, the imperative for water overrode notions of the sacred. Shallow bores were drilled on or near springs, while others were scooped out to enhance their flow. Charles Winnecke thought the desert "a most discouraging country to travel over, and for which a man obtains little or no credit … yet it is necessary to traverse and examine this country in detail, for one can never tell where and when an oasis may be found" (1894, p. 10). As the only source of permanent water west of the Mulligan River, the springs were important stepping stones on his push west into the present-day Northern Territory, and he visited most of the southern springs, from Beperry to Ethabuka. His descriptions of these springs are the only ones preceding the construction of bores and excavation of springs (Table 1), although Biparee, the far south-eastern spring of the Mulligan group (Figure 1), had already been fenced and "cleaned out" by early pastoralists. The party camped at Bookera (Boolcoorra) Spring before heading north-west into the dunefields, although their stay was not a pleasant one, with Winnecke recording that "a fearful hurricane, driving clouds of dust and sand into our faces has been blowing from the west for the past forty-eight hours" (1884, p. 6).

After Winnecke, numerous prospectors and travelling correspondents visited the springs, marvelled at and pondered their character, and considered their utility for stock. In 1884, a correspondent going by the name of 'Viator' visited the northern springs, along Sherbrook Creek above its junction with the Mulligan. He considered the springs "the most remarkable feature of the Far West", and described them as:

> … abound[ing] in all shapes, sizes, and descriptions; from the big mound with a stream gushing out, to the tiny cup of water no bigger than a horse's hoof. The water in most of the springs is delicious, though a few have a slight taste like gunpowder. There is not the slightest suspicion

> of salt in any of them, which is the more remarkable as they are all close to the Mulligan, which in that part of its course is the saltiest of salt creeks. What struck me most was the entire absence of mud springs, such as are so common in the spring country on the Paroo. Many of the mounds are covered with long reeds from 10ft to 12ft. high, and growing in a dense mass quite impenetrable. Others are clothed with a dark rush that I don't remember seeing anywhere else, and they look quite black at a distance. I was told that these were the best for water, and heard marvellous tales of tremendous gushes of water coming from the few that had been opened; streams suddenly spouting feet up in the air, &c., but I took all this *cum grano salis*. The best that I saw did not appear to me capable of watering more than 2000 cattle each in their present state, though no doubt the flow could be greatly increased (1884, p. 5).

In 1890, intrepid author A. J. Vogan faced "the terrors of the trackless waste" to explore these "curious springs of the Never Never" along the Mulligan River (Vogan, 1890, p. 582). Vogan was not averse to some poetic and artistic licence. Even accounting for some aquifer drawdown (see below), his estimate of 300 springs seems wildly excessive, and some of his sketches, including verdant gorges and fern-festooned cliff faces (Figure 2B), bear little resemblance to features on the ground. Nevertheless, he displayed a keen scientific interest in the springs, speculating on the processes behind these miraculous oases in the midst of "as dreary a wilderness of forbidding, barren wretchedness as one could find anywhere" (1890, p. 582). He suggested the springs might be of thermal origin, and were of greater flow and temperature in the geological past. Early pastoralists' plans for the springs were grand: "gradually to open up all these springs, and, collecting their libations by a system of ditches, keep a perennial stream flowing down the bed of the Mulligan" (Vogan, 1890, p. 582).

Although such lofty plans were never realised, the springs remained critical to pastoral life in this remote region well into the 20th century. In 1910, the *Pastoralists' Review* reported that each of six springs in the New Carlo group was capable of watering 1500 cattle, with the correspondent enthusing that "nothing impressed me so much in outback Queensland as these wonderful springs". A correspondent, 'Bendleby', visited Sandringham Station in December 1915 and was taken to see the "mud springs", which were regarded as "one of the most valuable assets on this station … [occurring] in some of the best country, with the feed right up to and around them. An artesian bore, the first in the district, had been put down and a grand supply of water obtained" (1916, p. 6). Bendleby recorded that "There were about 5,000 head of cattle on this [the neighbouring] station, which was known as Mungerebar, every hoof of which was, at the time of my visit, watering at one spring near the homestead, and within a short distance of the Sandringham boundary" (1916, p. 6).

The prolific inland correspondent Bill Harney, who spent time riding the rabbit fence near the Northern Territory border in the 1930s, wrote that:

> Water is a god in the dry lands. The native word for 'camp' is water, and the traveller when asking about the next camp would say: "How far the next water?" … Mud springs give life to that part:— Jewelery, Pelungra, Pinchamona, Pulchra with its lonely grave of the half-caste girl who was drowned there, Carlow flat with its extinct volcano and mass of mud springs on the bank of the Mulligan River (1946, p. 54).

Huts, stock camps and yards were built at springs, which were also essential to the construction and maintenance of the rabbit-proof fence; indeed, the fence was diverted from its planned line to pass Alnagata and Ethabuka Springs (Superintendent of the Gregory North Rabbit Board, 1897, p. 6). Boundary riders lived at a spring called Mirrica, 15 miles west of the Mulligan and 10 miles south of Ethabuka Spring (Harney, 1946). Montherida/Monteritta Spring was the last water along the fence heading out into the dunefields until Kuddaree Waterhole, some 150 km to the south. It was also, understandably, a much-awaited landmark on the return journey. Harney's boundary rider mate, Steve, recounted a harrowing tale about losing his pack camels and all his water some 50 miles from Monterrita. A dust storm descended, and his riding camel Trunga forged on into the wind and sand:

The wind roared on, the sand cut as with a lash, the stunted gidyeas brushed past in the march. Still Trunga kept on. At times he would fall to his knees, then up again and on his way. How long we travelled I do not know; I lost consciousness on that terrible night. Then Trunga stopped and lowered himself to the ground and refused to move. It was then I heard, faint and unmistakable, the suck, suck of a camel drinking. Was I mad? Was this an illusion to mock me? I fumbled with the straps and the calico, fell off his back, crawled to his head and felt. Water! We were at water. I drank and fell asleep. On opening my eyes in the daylight, I discovered we were at Moterrita spring (1946, p. 63).

Harney recounted his visit to the "hillbillies" at "Eitherbooka" (Ethabuka) Spring, the most isolated of the Mulligan springs, and the tragedy being played out against the backdrop of harsh red dunes:

… I looked out on the scene before me: the lonely life, the flowers tended on the grave nearby that marks the spot of another child who had died. "The camels were too rough for me," said Lil. "It was stillborn, but I had dreamt of it as a lovely child, so I asked Bill to give it a decent funeral. He growled at first; then we dug the shallow grave and there it lies. In the evening I often see it rise from the grave and play about. I show it to Bill. He says I'm mad but I know better, It is here," and she pats her breast; "it will return to me" (1946, pp. 63–64).

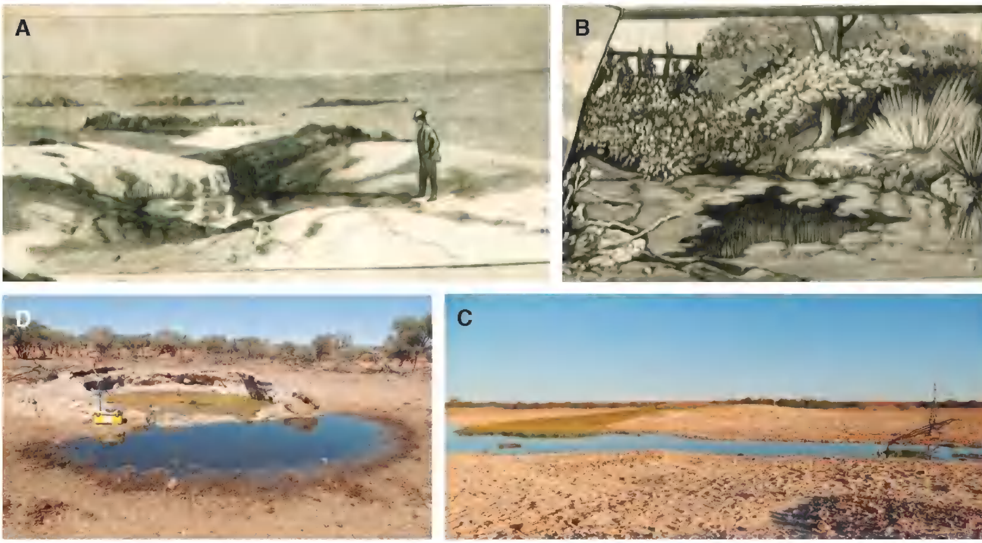
The old hut lived in by the people charged with maintaining that section of rabbit-proof fence was situated on the flat to the south of Ethabuka Spring, and was moved into Bedourie by the Smith family, former owners of Ethabuka, where it is now the dining room at the Bedourie Hotel. The springs remained mysterious and sometimes sinister to the early settlers:

Woe to the beasts that get bogged there; their struggles are in vain. Down they sink slowly to their doom; then after a time their bones are cast up again as though a giant ogre lived in the earth beneath that spot – some unknown type of monster devil or lion ant using these traps as a lure to entice the thirsty animals that they might be caught in its dangerous viscous mud. Oh, what a harvest it reaps in time of drought! (Harney, 1946, p. 55).

Table 1. Charles Winnecke's 1883 descriptions of the southern Mulligan River springs, in order of visitation. Winnecke's names for the springs, where they differ from contemporary names, are shown in brackets.

Spring	Winnecke's description
Beppery (Biparee)	"These springs are situated at the north end of a small claypan, which is surrounded by high spinifex sandridges. A few natives were encamped here, who, on our appearance, fled into the sandhills; the springs, three in number, are close together and similar to a great many mound springs on the overland telegraph line; they are slightly above the level of the claypan on little mounds; the water, although somewhat charged with soda, is drinkable. One of these springs has been fenced in and cleaned out, which has caused a small stream of water to flow into the claypan. I found it to run about 2,000 gallons a day; a far larger quantity of water could be obtained by further improving the spring" (11 September).
Bookera (Boolcoorra)	"… to another small claypan, containing several springs similar to those at Biparee; they are at present useless, being choked up with rubbish. It would require but a little labor [*sic*] to render these springs capable of watering a large quantity of stock. We camped at these springs, which the natives call Boolcoorra" (12 September).
Alnagata (Alnagatar)	"… a small spring which the natives call Alnagatar. We filled our kegs here in case this should be our last water" (12 September).
Cunja	"On ascending a high sandridge, to the east of Alnagatar Spring, I saw another small spring which the natives call Cunja. All these springs are similar and are situated in small claypans amongst high red sandhills; they could be made to water a large number of stock if properly developed" (12 September).
Tintagurra	"Another small claypan, containing several springs similar to Boolcoorra, and situated about half a mile to the N.W., amongst the sandhills, is called Tintagurra …" (12 September).
Ethabuka (Etabucka)	"… a small spring of very pure water, amongst a clump of timber situated between two high sandridges. The blackboy declared this spring to have no bottom; the surface is about ten feet long, six feet wide, and one foot deep. I can form no idea as to the quantity of stock it would water without a proper test" (12 October).

Figure 2. Vogan's 1890 sketches, (A) #1 "The Kendall Spring, near Carlo, Lat. 23°S, Long. 138°E" and (B) #5 "The Wandara Spring, showing silica basin, on the Mulligan River". The Kendall Spring sketch seems most likely to be Crater Spring (C), while the most likely candidate for Vogan's Wandara Spring is Natural Well (D).



On still desert nights, lonesome travellers could sometimes hear Bulkra (Bookera) Spring moaning over the sandhills: "Bulkra, Bulkra, the sound of water and gas escaping from the mud" (Harney, 1946, p. 55). Bookera's cry was known to the Mulligan bushmen, as recounted by boundary rider Steve during his aforementioned dust-storm journey to Monterherida:

> The sun became a red ball in the sky, then gradually faded away; the sand-storm rose to a violent pitch; it was so dark even at midday that I couldn't see a few feet past old Trunga's ears. I was becoming weak when old Trunga faltered and threw himself to the ground. Frantically I beat him to urge him on, as I myself was failing from want of water and sleep. I could hear distant waters gurgling nearby and often plain and distinct the welcome sound of "Bulkra" coming over the wind, though only reason could tell me it was an illusion and a snare. Imagination is a terrible curse to the thirsty man; the mirage in the distance lures him on to his doom; the voices call from the subconscious mind; he hears the welcome sound of water and so he rushes onward to destruction (1946, p. 63).

Remains of old stock camps and yards are found near Old Carlo, Pitchamurra, Montherida and Bookera Springs. There are remnants of old fences around many springs, presumably to prevent stock bogging, and troughs and defunct windmills at some. There are graves on low sand dunes near Currabinta and Ethabuka Springs, which respectively read: "IN MEMORY BLACK BOY JACKEY BALKIN DIED 23 JUNE 1917 AGED 14 YEAR" and "21 October 1919. In loving memory of Matthew Edward Corkhill, missed by his loving parents". The latter was possibly a child of the couple Bill Harney met at the spring some time in the 1910s.

Despite their importance to the early pastoral economy, only one spring group – Cookeygerima Springs – is marked on the survey run plan from ca 1890, and fewer than a third are marked on the later '4 mile' series (Figure 3) drawn in 1928 and 1957.

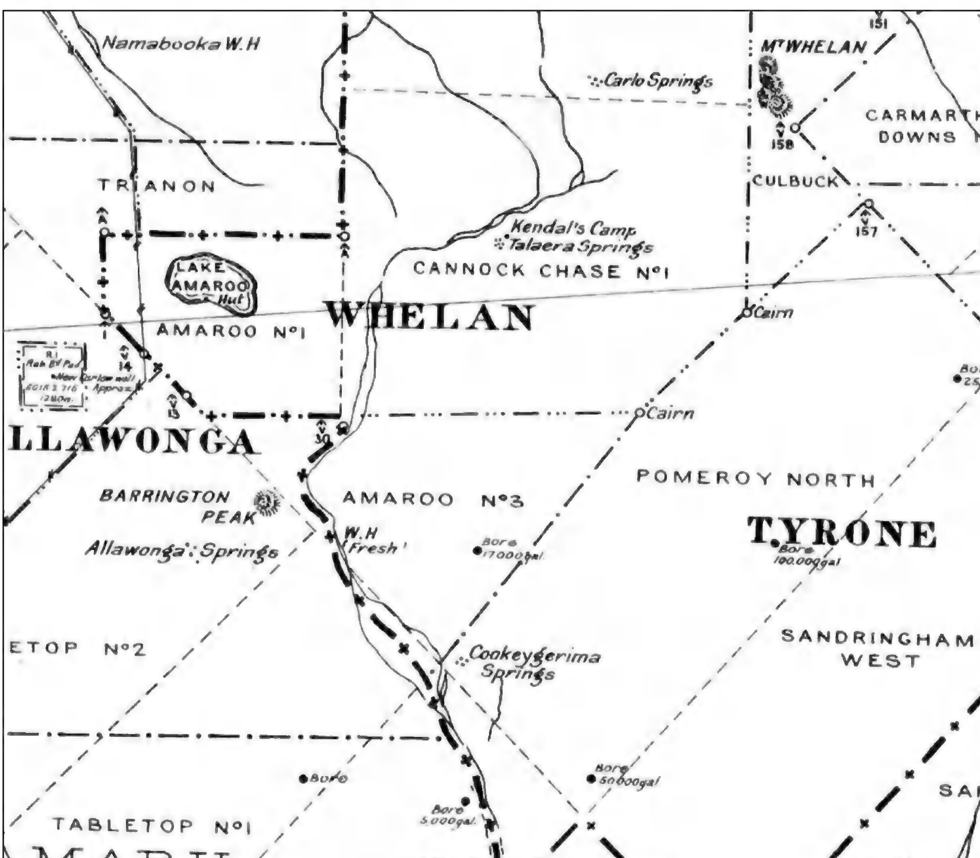
Current Knowledge and Status

There are 34 main spring groups in the Mulligan River supergroup, as well as many small soaks and mounds, covering an area of about 70 × 40 km

along the upper Mulligan River and extending into the dunefields to the west (Figure 1). Our 2013 survey mapped over 90 individual vents, with individual spring wetlands ranging in size from <1 m^2 to about 1350 m^2. The southern springs (Alnagata, Cunja, Bookera, Beppery and Ethabuka; Figure 1) form pools on claypans in swales between linear sand ridges typical of the Simpson Desert. They often occur on small mounds near the edges of swales.

The exception is the mysterious Mirrica Spring (Figure 1), which is marked on 4-mile maps and described by Bill Harney as being 10 miles south of Ethabuka Spring, 15 miles west of the Mulligan River, on the netting fence. The Smith family, long-term residents and graziers of Ethabuka, knew Mirrica Spring as a small rockhole in an outlying outcrop of Tertiary sandstone, where the Hooray Sandstone is pinched out or thin against the Toomba Fault (Reynolds, 1964). It was apparently excavated and no longer flows, and there are disused flume pipes lying nearby. The rockhole and surrounding country do not have the appearance of a GAB discharge spring, and the location on the map and from Harney's description places it further south amongst low mesas. Extensive searching in this area has found only a one-metre-deep ephemeral rockhole at the base of a small cliff. Assuming the location known by the Smiths is correct, Mirrica Spring has ceased to flow and its situation in rock outcrop is unlikely for a discharge spring (Fensham et al., 2016).

Figure 3. 4 mile series 1, sheet 12B (1928) showing Carlo, Talaera, Allawonga and Cookeygerima Springs.



We were unable to locate a spring mentioned by Winnecke, apparently to the west of Bookera. After leaving their camp at Bookera in September 1883, Winnecke's party got disoriented in a dust storm – Blucher, their Aboriginal guide, eventually conceded that he was lost – and their course was "very irregular and subject to many abrupt turnings" (Winnecke, 1884, p. 6). Winnecke recorded that they "passed Tintagurra Springs and another small spring at about one and a half miles; this last spring seems to be a favourite camping place for the natives; probably the water is slightly better than that in the other springs". Due to their irregular course, it is difficult to know where this small spring is located, but their ultimate course was west to Montherida Spring. During our 2013 survey, we examined two claypans west of Bookera, but neither had the appearance of springs or soaks. There is a small scald approximately 1.5 km north-west of Bookera that was not checked but is tentatively assigned as the site of this "Camp Spring".

The remainder of the springs are clustered in two main groups, with some outliers, along the upper Mulligan River and its tributaries, chiefly Sherbrook Creek (Figure 1). They occur on the broad samphire flats of the Mulligan River and Sherbrook Creek floodplains, and some become connected to these watercourses during floods. These watercourses cut through extensive rolling gibber plains, although Allawonga, Grindstone and Pitchamurra abut dunefields. Some of these springs appear to seep from beneath calcareous rocky material, which forms low mounds above the springs. Wandera Spring occurs just above a small waterhole, which it feeds, while Wongitta Spring is situated on a scalded rise above the western shore of the ephemeral Lake Wongitta. In addition to the main springs, there are many small soaks marked by bore-drain sedge (*Cyperus laevigatus*) and/or common reed (*Phragmites australis*), with damp sand and occasionally tiny puddles of water. Active, wobbly mud springs were recorded at two sites (Lobbs Spring and on the north-western edge of the Carlo Flat group; Figure 1), both in close proximity to water springs.

Unlike other spring groups (Fairfax & Fensham, 2002; Powell et al., 2015), the majority of springs (30 of 34 main springs) in the Mulligan supergroup remain active despite the sinking of many bores in the area (Figure 1). Only three springs are now inactive: Currabinta near the centre of the supergroup, where a bore was sunk in 1890 on top of the spring; Tintagurra in the south, which was probably located on a scalded claypan between dunes where there is a scalded mound and abundant stone artefacts; and Mirrica, whose hydrogeology remains mysterious (see above). The status of Camp Spring (see above) is unknown. It is likely that the flows and wetland sizes of others have been reduced due to declining aquifer pressure. Many bores within 20 km of the springs that tapped the Hooray Sandstone ceased to flow within a century (e.g. registered bore numbers 1661, 776, 14146), and spring water once flowed Sylvester Creek for six miles (Purcell, 1892), indicating substantial decline in groundwater pressure.

The springs appear to display considerable natural dynamism. Some of the smaller soaks and mounds on the Mulligan River floodout are apparently being inundated with sand, and may ultimately become sandy mounds where water no longer reaches the surface. The springs on Carlo Flat on Glenormiston (Figure 1) demonstrate this process. Wind-blown sand accumulates around the patches of perennial vegetation around springs and soaks on an otherwise unvegetated plain. This raises the spring to a mound but eventually seals the flowing vent. At one site a now-extinct spring has been completely buried, with only old timber fence posts marking its former existence (Figure 4). Vogan (1890) described this process:

> These mud springs appear liable to be choked from their very life-giving qualities. They become the battle-ground of a fierce floral struggle for existence, while all around is oft-times nearly a desert; and the final engagements terminate in rushes of some kind taking up their waving tasselled position on the moist mounds. These rushes … crowd upon each other until their close proximity causes the decrease of all, when a fresh battle begins. The matted enterprising roots, the falling leaves, the decaying stalks, also the sand that the growing mass has collected and deposited during the dust storms from the south, would seem to at last quite choke up the outlet of the spring. Remains of such pugged-up mounds are not wanting. The natives also, in bygone

> times, have been instrumental in closing many of them – it is supposed from superstitious motives … (1890, p. 582).

There are inactive carbonate mounds and patches of travertine on the Mulligan River plain between Lobbs and Cookeygerima Springs (Figure 1), and in dune swales to the west. These probably mark the sites of fossil springs that may have been extinct prior to pastoral settlement. One of these travertine mounds was active in 2013, with wobbly mud on top, suggesting that these apparently long-extinct springs can become 'reactivated'. Sunset Spring to the north-east of Kidman Bore is at the base of a low dune and in 2013 had the appearance of a new or re-activated spring. There is an arc of travertine around the spring. High concentrations of grindstones, cores and flakes around springs that remain active but with no free water also hint at this dynamism.

Comparisons between the 1999 and 2013 survey periods suggest reactivation or increase in wetland area at some springs due to increase in aquifer pressure following bore capping (Klohn Crippen Berger, 2016). New spring mounds had popped up adjacent to the main springs at New Carlo. Numerous springs in the north of the group on Glenormiston were flowing more and creating larger wetlands in 2013 than 1999. In 1999, water was found at 80 cm below the ground surface in Cookeygerima Spring; in 2013, the mound was moist on the surface and dotted with *Cyperus laevigatus* (Figure 5); old fence posts around the spring suggest that the spring was once a hazard to stock, indicating greater flow in the past. Lobbs Spring was a tiny puddle of water, 20 cm in diameter × 2 cm deep in 1999, with a second soak (no free water) 25 m to the west. In 2013, it had a wetland area of 8 × 5 m, comprising a mound of *Cyperus laevigatus* and a pool of free water, and 25 additional vents (some with free water, some small soaks and some mud springs) were documented, running north–north-west for about 4 km along the Mulligan River plain. These have appeared since a nearby bore was capped in the mid-1990s. Future monitoring of springs in this area will provide further insights into spring recovery and emergence following bore capping.

Ecology and Conservation

Springs in the Mulligan River supergroup are generally small, with a median wetland area of 12 m^2. Half of the springs with wetlands cover areas <10 m^2, and only five have wetlands at least 1000 m^2 in area. Their waters are generally alkaline (average pH 8.5, std.dev. 0.85, range 7.0–10.0; $n = 35$) and range from fresh to brackish (average 5,318 μS/cm, std.dev. 6,454 μS/cm, range 1,044–29,100 μS/cm).

Desert rainbow fish (*Melanotaenia splendida tatei*), glass fish (*Ambassis* sp.) and Lake Eyre hardyheads (*Craterocephalus eyresii*) have been recorded in the springs on the Mulligan/Sherbrook Creek floodplain. The hardyheads in New Carlo Spring are thought to be the source population for the upper Mulligan (Adam Kerezsy, fish ecologist, pers. comm.). The springs are also havens for wetland birds – clamorous reed warblers, white-necked herons, grey teal, black-fronted dotterels and spotted crakes were among those observed at the springs in May 2013.

Figure 4. Spring dynamics on Carlo Flat, 2013; from left: active spring, Sand Spring (augmented by recent rain); Wandera mound with *Cyperus laevigatus* but no free water; and Frankie's Spring, now buried with only old fence posts marking the site of a former spring.

Figure 5. Cookygermia Spring in 1999 (left)), when water was reached after digging to 80 cm depth, and in 2013 (right), when the surface was moist and dotted with the sedge *Cyperus laevigatus*.

Camera traps confirmed the importance of the springs to zebra finches, budgerigars, galahs and other granivorous birds, while corvids, emus, bustards and brolgas were regularly recorded congregating and bathing in the associated wetlands. Common raptors such as spotted harriers, wedge-tailed eagles and brown falcons were recorded visiting many of the springs, with grey falcons often seen drinking and hunting around the most westerly springs.

The springs are reliable watering points for native mammals needing to drink at regular intervals (Figure 6). Dingoes and red kangaroos are able to persist during dry conditions with access to these permanent waters. The springs also provide refuge for many introduced species such as foxes, cats, camels and pigs (Figure 6), with considerable impact on spring vegetation and morphology by the latter two species (see below). Interestingly, a number of reptile species including bearded dragons, perentie and sand goannas have been observed utilising the springs, often drinking from small pools, but most likely taking advantage of the invertebrate prey associated with the spring habitats.

No plant or fish species are endemic to the Mulligan River supergroup; however, GAB scald endemics *Trianthema* sp. (Coorabulka R.W. Purdie 1404) and *Sporobolus partimpatens* are common around 23 and seven spring groups, respectively. *Cyperus laevigatus*, which is restricted to GAB springs and bore drains in inland Queensland, was recorded in 38 spring wetlands in 22 spring groups, representing highly disjunct populations. The sedge *Fimbristylis ferruginea* was found only at Post and East Springs on Glenormiston; it is restricted to a few GAB springs in western Queensland, although it is widespread in coastal areas. Disjunct populations of the common reed *Phragmites australis* and bulrush *Typha orientalis* were each recorded at seven spring wetlands in four northern spring groups. No endemic snails or other invertebrates were recorded in the springs, although red worms seen at Blacks and Allawonga Springs warrant further investigation. This lack of taxonomic or phylogenetic endemism contrasts with other GAB spring groups, and the Mulligan River springs are also characterised by lower species richness and taxonomic diversity than most other spring groups (Rossini et al., 2018).

Many of the major springs are highly modified, particularly those that occur in dune swales in the south of the supergroup, where five of the seven major spring groups have been excavated or had major structural modifications. Alnagata North and Ethabuka have large flumes inserted into the centre of their wetlands, from which water was piped to hollows dug nearby, while Beppery has a stone well and rusty bore in the centre of the largest spring. The northern and central springs on the Mulligan River plains are less modified, although the New Carlo, Natural Well and Blacks Springs all appear to have been excavated to improve cattle access. Date palms have been planted at three northern springs, but photos and observations between 1999 and 2013 suggest that they are not spreading. There are no detailed descriptions or biological collections from the springs prior to modification, and it is possible that endemic or unique spring species were lost due to modification of wetlands and aquifer drawdown reducing the size and perhaps permanence of some springs.

Figure 6. Utilisation of Mulligan River springs by both native (top) and introduced (bottom) fauna. Images taken from motion sensor cameras set up at the springs between October and November 2012.

The springs remain a focus for cattle grazing, with most of the larger springs showing some evidence of cattle damage in 2013, including eight that were heavily impacted by trampling. Some springs on Glenormiston are now fenced from cattle, while the springs on Ethabuka have not been grazed since its acquisition by Bush Heritage Australia in 2004. Ethabuka and Alnagata North Springs have been fenced from camels, and the recovery of vegetation around the springs has been pronounced. There was evidence of pig damage at 34 of the 64 springs with wetlands. This was affecting >50% of the spring wetland area at seven springs, but these surveys were conducted after wet seasons, and pig impacts on the springs are known to intensify in dry times. Spring vegetation seems to be able to recover from even severe grazing and trampling disturbance. Some springs that were heavily impacted by cattle and pigs in 1999 showed little sign of disturbance and were covered in dense vegetation in 2013, while others that were unaffected in 1999 were heavily impacted by cattle in 2013. Allawonga Spring was fenced in 1999, allowing a dense thicket of *Phragmites australis* to dominate the spring, which became entirely devoid of free water (Figure 7). This provides an example similar to experiences in South Australia, where complete exclusion of grazing disturbance with fencing may not be the most appropriate form of spring management (Fensham et al., 2010). Fencing needs to be assessed on a case-by-case basis and should include gates to allow potential occasional disturbance.

As discussed above, new springs seem to be emerging, and some old ones reactivating or becoming larger, probably due to restored aquifer pressure with bore capping. There are no doubt other springs yet to be 'discovered', although they were no doubt well known historically to the Wangkamadla

people – as evidenced by the artefacts around some of the more remote springs located in 2013. There are many claypans to the west of the Mulligan River on Marion Downs, and it seems likely that some unvisited claypans harbour soaks and perhaps small springs. Although the area bounded by Cookeygerima Spring, Currabinta Bore, Kidman Yards and Lobbs Bore (ca 10 × 6 km) has been reasonably thoroughly surveyed, it is likely that numerous small vents have been missed.

Figure 7. Allawonga Spring 1, February 1999, when fenced to exclude cattle and supporting a dense thicket of *Phragmites australis* without free water (left) and trampled by cattle and pigs in March 2013 following destruction of fence, but with free water present (right).

Concluding Comments

Flumes, excavations, cattle and the devastating impact of colonisation on the traditional custodians of the springs make communing with the Mulligan River spring Oracle more difficult today. However, there remains something inherently compelling about this water, travelling thousands of kilometres over perhaps tens of thousands to millions of years, to finally rise and create oases between the fiery red dunes and along the ghostly white flats of the Mulligan River. Future work should focus on better elucidating their hydrogeology, particularly with regard to projected water use by extractive industries in the Eromanga Basin (Klohn Crippen Berger, 2016) and understanding spring dynamism and apparent recovery of some springs with bore capping. Detailed archaeological work at the springs would provide further insights into Aboriginal use of the springs, including their place in the broader cultural landscape and potential significance to Aboriginal trade networks in inland eastern Australia.

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Max Tischler has been working in the Australian arid zone for the past 22 years, on a range of projects focused on the ecology of small mammals, reptiles, fish and birds. He is the Chief Scientist for Australian Desert Expeditions, a Registered Environmental Organisation using traditionally outfitted pack camels to explore and document the natural history of the remote inland.

Rod Fensham has conducted extensive research on ecology and conservation directed towards the preservation of the Queensland bush. He has been working on spring ecosystems for 20 years and has contributed to many aspects of their conservation including engaging GABSI with springs protection, contributing to numerous regional plans, and managing Edgbaston station for springs conservation with Bush Heritage Australia.

Caridina thermophila, an Enigmatic and Endangered Freshwater Shrimp (Crustacea: Decapoda: Atyidae) in the Great Artesian Basin, Australia

Satish C. Choy[1]

Abstract

Only one species of freshwater shrimp, *Caridina thermophila*, has been recorded from the Great Artesian Basin (GAB) springs and associated wetlands in central Queensland. The species seems to be endemic to Queensland, has a restricted distribution and, whilst it is listed as Endangered in the IUCN Red List of Threatened Species, is not specifically protected under any Australian state or federal legislation. Although *C. thermophila* was first described from hot-water springs, it is now known to also inhabit much cooler waters, and hence its temperature tolerance range is quite broad. Apart from its general ecology and associated spring communities (many of which include rare and endangered endemic species), very little is known about the population dynamics and resilience of this species, particularly in relation to anthropogenic pressures and climate change. It is recommended that this species be specifically protected under national legislation, and a conservation plan be developed and implemented to ensure its long-term survival.

Keywords: Great Artesian Basin, springs, wetland, shrimp, *Caridina thermophila*, endemic, endangered

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Introduction

Caridina thermophila (Figure 1) was first described by Riek (1953) along with several other freshwater atyid shrimps from Australia. All his *C. thermophila* specimens, including the types, were collected on 27 May 1945 from an artificial bore drain in Muttaburra, western Queensland. He mentioned that the habitat was quite "remarkable" and the shrimps were "simply swarming". He also mentioned that "the water emerging from the ground was too hot for normal life (and unpleasant to stand in for any considerable time) but after flowing for some distance it had cooled sufficiently to support life". The shrimps were most abundant where the water was still "too hot for comfortable wading", hence the species descriptor "*thermophila*". Riek (1953) also mentioned that "only two of the many specimens collected were ovigerous" but thought that although May was rather too early to expect eggs, it seemed most likely that the species bred in this hot-water habitat.

Caridina thermophila is one of the many endemic species that occur in the springs of the Great Artesian Basin (Fensham et al., 2010). Its status has, however, been somewhat questionable and the species has not been treated as uniquely as other endemic species (e.g. Fensham & Fairfax, 2005; Rossini et al., 2018). This may be due partly to its being rather abundant whenever it occurs, and partly because of its dubious taxonomic status and perceived widespread distribution. Other species that often co-occur with *C. thermophila* include the endangered endemic fishes, the red-finned blue-eye (*Scaturiginichthys vermeilipinnis*) and the Edgbaston goby (*Chlamydogobius squamigenus*). Invertebrates that co-occur include annelids, molluscs, amphipods, isopods, and a variety of insect nymphs and larvae such as caddisflies, mayflies,

damselflies and beetles (Ponder et al., 2010; Rossini et al., 2018). The exotic eastern gambusia or mosquito fish (*Gambusia holbrooki*) is also known to infest these artesian springs (Fairfax et al., 2007). However, its impact on *C. thermophila* is not known.

Taxonomy

Based on its morphology, *Caridina thermophila* clearly belongs to the genus *Caridina* and is a valid species (Riek, 1953). Recent genetic studies have confirmed its validity as a species (Page et al., 2007a) and being epigean (Page et al., 2007b). Whilst there is another undescribed species of *Caridina* in the Lake Eyre Basin (*C.* sp. LE, from Algebuckina Waterhole, Neales River, in the Lake Frome area, South Australia), it does not belong to the same genetic clade as *C. thermophila* (Page et al., 2007a; Short et al., 2019). Interestingly though, there is a newly described species, *C. biyiga*, from Leichhardt Springs, Kakadu National Park, Northern Territory (Short et al., 2019), and two undescribed species (*C.* sp. NT1 from Melville Island, Northern Territory, and *C.* sp. WA3 from the Pilbara, Western Australia) that belong to the same genetic clade as *C. thermophila* (Page et al., 2007a; Cook et al., 2011; Short et al., 2019).

Riek (1953) provided a detailed morphological description of *Caridina thermophila*. It is a relatively small but robust animal with a short rostrum and stout appendages. Younger animals, particularly the males, are a bit more slender. Based on specimens in the Queensland Museum (Reg. No. QM W17177) collected from another locality (Edgbaston Station Springs at Homestead, coll. 15/5/91), some of the morphological features are much more variable than those described by Riek (1953). For example, the rostrum can be variable in length and shape, its dorsal teeth can range from 19 to 25, and its ventral teeth can range from 2 to 6. Additional features not described by Riek (1953) include: no appendix interna on the first pleopod of males; carapace depth 0.80–0.83 times the post orbital carapace length (CL); rostral length 0.61–0.72 CL; antennular peduncle length 0.68–0.72 CL; sixth abdominal segment length 0.44–0.58 CL; and telsonic length 0.56–0.7 CL.

An interesting feature that Riek (1953) reported was that one of his specimens had an exopodite on the first left pereiopod. However, it was absent on the right periopod. Riek (1953) mentioned that this condition approached that which was "normal" for the genus *Caridinides* Calman, 1926, where both first pereiopods have exopodites. It has now been demonstrated that, whilst *Caridinides* was somewhat unique in having these exopodites, it is genetically no different from the genus *Caridina* H. Milne Edwards, 1837 (Page et al., 2007a; De Grave & Page, 2014).

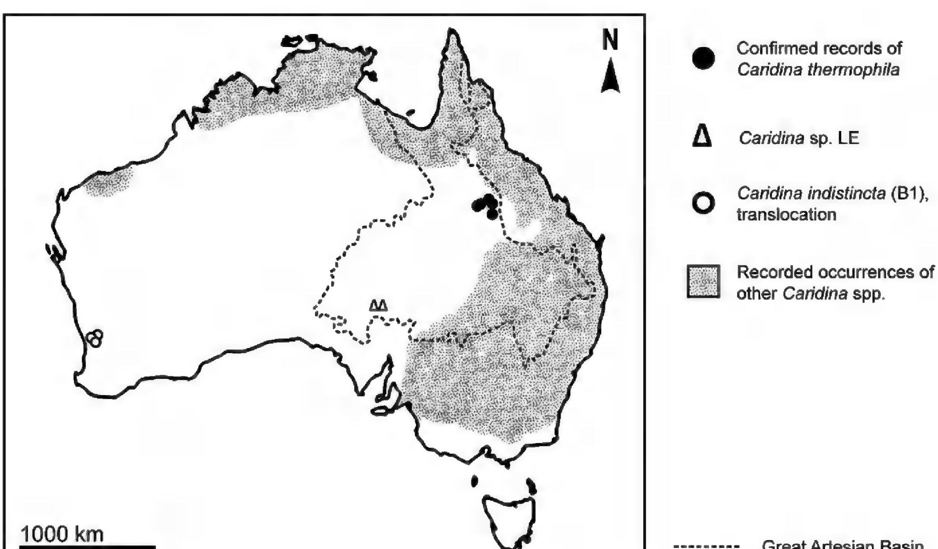
Figure 1. *Caridina thermophila*, photographed from Edgbaston Reserve (Photo: Renee Rossini (www.bushheritage.org.au/blog/edgbastons-hidden-charms)).

Caridina species are notoriously difficult to identify based just on their morphological features. This is because they exhibit great morphological plasticity based on the environment in which they live, and many of the features used to separate species taxonomically can be highly variable (Page et al., 2005; De Mazencourt et al., 2017; Choy et al., 2019). A combination of morphology, molecular techniques and ecology seems to be the best way to resolve many of the taxonomic uncertainties, and this is now becoming a standard approach (De Mazencourt et al., 2018; Choy et al., 2019). Molecular techniques are also allowing evolutionary and biogeographic elucidations (Page et al., 2008). Based on such techniques, it seems that *C. thermophila* has evolved and adapted to living in aquatic habitats created by artesian springs, along with many other rare and endangered endemic species of flora and fauna in artesian springs (Fensham et al., 2010).

Distribution

According to the *Atlas of Living Australia* (www.ala.org.au), there are 59 records of *Caridina thermophila* from 4 collection datasets. These are Australian Museum (4 records), Queensland Museum (3 records), Museums Victoria (43 records) and South Australian Museum (9 records). Based on these and other confirmed collections, the current known distribution of *C. thermophila* includes artesian springs around Edgbaston Station, about 15 km south-west of Muttaburra (22.733°S, 144.427°E) and Muttaburra (22.600°S, 144.550°E), as well as artesian springs about 30 km north-east of Barcaldine (23.280°S, 145.24°E) and artesian springs about 30 km north-east of Aramac (22.730°S, 145.417°E). All these sites are about 100 km from Aramac, about 100 km north to east of Longreach, and cover an area of only about 70 km^2. All of these springs are in the Great Artesian Basin and the Cooper Creek catchment of the Lake Eyre Basin (Figure 2). A detailed distributional map of the 59 museum records can be found at https://spatial.ala.org.au. There are also unconfirmed records from Yowah Springs in the Eulo complex, Elizabeth Springs and the Einasleigh Upland springs (Rossini, pers. comm.). Even if these and possibly other distribution records were to be confirmed, it is clear that *C. thermophila* is endemic to Australia, occupies a rather unusual niche, and needs to be recognised as such. The current knowledge of the exact distribution of *C. thermophila* is still very unclear, and concerted effort is required to study its taxonomic status, genetic clades, distribution, ecology and conservation status.

Figure 2. Distribution of *Caridina thermophila* in relation to other *Caridina* species in Australia.



Riek (1953) commented that "a study of the distribution of this species would be most interesting for bores are artificial and of recent origin and not a high percentage are so hot". He also commented that "given that the eyes of *Caridina thermopila* were well developed, the species was unlikely to be subterranean". Studies since then suggest that *C. thermophila* is found in natural artesian springs, in cooler waters, and it is not subterranean (Fensham & Fairfax, 2005; Page et al., 2007b). Riek (1953) also reported that there was a decrease in the concentration of specimens as one proceeded downstream, from hotter to colder water. Rossini et al. (2015) found that Atyidae (= *C. thermophila*) were more abundant in the deeper "pool" areas than in the shallower "tail" areas of the springs they studied.

Ecology

As discussed above, *Caridina thermophila* has been reported from several localities in central Queensland. The artesian springs and associated wetlands in which it occurs are also home to many other endemic species of plants and animals (Fensham & Fairfax, 2005), some of which are listed under Endangered Species legislation and the subject of recovery plans (Fensham et al., 2010). Despite this, the basic taxonomic and ecological information of many artesian spring invertebrates is lacking (Rossini, 2018). It has been reported that *C. thermophila* has been excluded from most studies because the taxonomy of *Caridina* within Australia has generally been poorly resolved (Rossini et al., 2018), and that there was currently not enough evidence to suggest it is endemic (Ponder et al., 2010; Rossini et al., 2018). A compilation of studies, however, indicates that *C. thermophila* is not only endemic to central Queensland, it is confirmed only in the Barcaldine spring supergroup (Choy, pers. ob., Choy & Howitz, 1995; Fensham & Fairfax, 2005; Page et al., 2007b).

The aquatic habits in which all artesian spring species occur have been described as isolated aquatic "islands" in a semi-arid landscape (Kerezsy, 2013). Most habitats are less than 50 m wide, with depths of about 0.1 m. Water quality is highly variable, from fresh to somewhat saline, near zero to saturated dissolved oxygen, near freezing water temperatures in winter to about 40°C in summer. In these habitats, *Caridina thermophila* lives as an opportunistic omnivore, making use of whatever resources are available for its survival. Reik (1953) noted different distributional patterns of *C. thermophila* even within a single spring. This pattern appears to be driven by the interaction between different environmental conditions in different microhabitats and the environmental tolerances of the species. However, the interactions are not likely to be simple (Rossini et al., 2017).

An interesting feature of *Caridina thermophila* is that the eggs are relatively large (about 0.5 mm wide and 0.8 mm long) and few (<30) per brood. This suggests that larval development occurs mainly within the eggs, which then hatch as advanced larvae, and so the planktonic stage is short or non-existent (Hancock, 2008; Lai & Shy, 2009). Such abbreviated or direct larval development is a feature of many inland and endemic species of aquatic invertebrates (Morton & Britton, 2000; Darragh, 2002). In contrast, coastal and more widespread species tend to have a prolonged larval stage (Pechenik, 1999). The former strategy results not only in less predation mortality but also in restricted distributions (Obrebski, 1979; Choy, 1991). It is therefore likely that *C. thermophila* may not be as widespread as some unconfirmed records suggest.

Conservation and Management

Caridina thermophila is endemic to Queensland and seems to have a very restricted distribution. It is currently confirmed only from Spring Complex Numbers 49 (Cares), 65 (North), 80 (Umbridge) and 81 (Caring), all of which are in the Barcaldine North Great Artesian Basin Water Resource Plan Management Area (GABWRPMA) and are listed under the EPBC (Australian *Environment Protection and Biodiversity Conservation Act 1999*) (Fensham & Fairfax, 2005). These spring complex and supergroup names are somewhat different from those listed in Appendix S2 in Rossini et al. (2018). *C. thermophila*'s listing in Spring Complex Number 156 (Yowah Creek) in the Warrego East GABWRPMA is likely to be erroneous. No specimens have been sampled from here recently (Peter Negus, pers. comm.), and even if they were, they would most likely be another species of *Caridina*.

Caridina thermophila is listed as Endangered in the IUCN Red List of Threatened Species (De

Grave et al., 2013), yet it does not have an EPBC status or a NCA status (under the *Queensland Nature Conservation Act 1992*). Even under the Great Artesian Basin Water Resource Plan (GAB WRP) the species is listed just as "other species of interest" (Fensham & Fairfax, 2005). However, the communities within which this species occurs are listed as Endangered under Commonwealth and Queensland legislation (Table 1).

Whilst the species itself has no direct protection through its own state or national listing, it is somewhat protected through the status of the communities within which it occurs. However, most complexes of high conservation value remain outside of conservation reserves, and the endangered species status of many taxa, particularly the invertebrates, remains unassessed (Rossini et al., 2018). There is also a national recovery plan for these communities (Fensham et al., 2010), and *Caridina thermophila* also has a "high" Back on Track status, meaning that it has a high priority amongst Queensland's native species to guide conservation management and recovery. Many species that co-exist with *C. thermophila* are also rare and endangered (e.g. red-finned blue-eye (*Scaturiginichthys vermeilipinnis*) and the Edgbaston goby (*Chlamydogobius squamigenus*). Some protection is therefore offered through the protection of these fish species. However, the GAB springs and wetlands in which these species occur are subject to climate change, competing human interests (e.g. aquifer drawdown, agriculture and mining) and introduced fauna (e.g. eastern gambusia (*Gambusia holbrooki*), cane toad (*Rhinella marina*) and redclaw crayfish (*Cherax quadicarinatus*)), all of which pose great danger to this and other species, as well as their communities (Clifford et al., 2013; Green, 2013).

It has been suggested that the most appropriate level for the management of endemic species are the spring complexes (Green, 2013). Whilst this may be the best overall management approach, it is imperative that *Caridina thermophila* is locally and nationally recognised, listed as an endangered species, and that a specific conservation plan be implemented. It has been suggested that *C. thermophila* specimens be subject to relocations, be made available to private breeders and even introduced to the aquarium trade. Whilst these may be viable options, such strategies would risk genetic contamination and hybridisation (von Rintelen et al., 2007).

Since very little is known of the exact taxonomic status, distribution, demography (population size, structure, natality and mortality rates) and ecology of this species, it is recommended that further research into these aspects be implemented to support its management and conservation. However, all field collections of this enigmatic species should be minimised during specific research projects, as well as from broader-scale artesian spring studies, and all sampling strategies should consider returning all specimens alive and well to the localities where they are collected.

Emerging Issues

The Great Artesian Basin is one of the world's largest underground water reservoirs, but despite its size, age and persistence to date, it is facing many threats, both natural and anthropogenic. Its water utilisation since European colonisation has led to unsustainable practices in many areas, hence the desire of stakeholders and governments to commence appropriate forms of conservation and management. Whilst management strategies are working in some parts of the GAB, upcoming threats make them very challenging. The flora and fauna that are reliant on the GAB water and habitats are facing even greater threats and, whilst conservation efforts are being implemented, it is the larger and more iconic species that are getting the most attention. Smaller and less-conspicuous species are being neglected, and some may be disappearing even before being discovered and formally named by science. Species such as *Caridina thermophila* have largely been ignored, mainly because of their uncertain taxonomy, distribution, ecology and conservation status. Whilst broad management strategies to conserve spring complexes and iconic species will no doubt benefit non-target co-inhabitants, specific conservation status and management strategies should be implemented for all endemic species, including *C. thermophila*; and more nature reserves, such as those of Bush Heritage Australia, should be set up to protect such species. Unless these steps to protect endemic spring species are taken now, for many species it will be "death by a thousand cuts" and many of them will disappear while we watch and wait.

Table 1. Communities in which *Caridina thermophila* occurs, and their conservation status.

Community	Conservation status	Legislation
The community of native species dependent on natural discharge of groundwater from the Great Artesian Basin	Endangered	*Environment Protection and Biodiversity Conservation Act 1999* (Commonwealth)
Springs in discharge areas of the Great Artesian Basin, and not located in Tertiary aquifers	Endangered	*Vegetation Management Act 1999* (Queensland)
Regional Ecosystem 2.3.39, spring wetlands on recent alluvium	Endangered	*Vegetation Management Act 1999* (Queensland)
Regional Ecosystem 4.3.22, springs on recent alluvia and fine-grained sedimentary rock/shales	Endangered	*Vegetation Management Act 1999* (Queensland)
Regional Ecosystem 6.3.23, springs on recent alluvia, ancient alluvia and fine-grained sedimentary rock/shales	Endangered	*Vegetation Management Act 1999* (Queensland)

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Author Profile

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Fishes of Australia's Great Artesian Basin Springs – An Overview

Adam Kerezsy[1]

Abstract

Patterns of fish distribution within Great Artesian Basin springs fall into two distinct categories: the opportunistic colonisation of springs by widespread riverine species following flooding, and long-term habitation – and speciation – within isolated spring complexes by fishes endemic to certain spring complexes. The endemic fishes of Australia's Great Artesian Basin springs persist in what some would consider the most unlikely fish habitats imaginable. Within predominantly hot and dry landscapes, they inhabit the only reliable wet areas, which are frequently the same temperature as the surrounding plains and as shallow as the body depth of some of the species. There are seven narrow-range fish species endemic to Great Artesian Basin springs: the Dalhousie catfish (*Neosiluris gloveri*), Dalhousie hardyhead (*Craterocephalus dalhousiensis*), red-finned blue-eye (*Scaturiginichthys vermeilipinnis*), three localised species of gobies (*Chlamydogobius gloveri*, *C. micropterus* and *C. squamigenus*) and the Dalhousie mogurnda (*Mogurnda thermophila*). These species occur at only three locations: Dalhousie in South Australia; and the Pelican Creek and Elizabeth Springs complexes, which are both in Queensland. An eighth species, the desert goby (*Chlamydogobius eremius*) has a wider range across multiple spring complexes in South Australia. All GAB endemic spring species should be considered endangered due to their small ranges and small populations; however, their formal status varies widely between state, national and international legislation and/or lists. Additionally, all fish endemic to GAB springs are threatened by a broad suite of factors that endanger inland aquatic ecosystems, such as water extraction, pollution, and the possibility that alien or unwanted species may become established. Persisting as they do in such unique and specialised habitats, the study of these GAB fish – and all GAB springs endemics – can reveal much about evolution, speciation and resilience. Although there is a growing recognition that conservation of the fishes and their habitats is important, this is complicated by the confusing variability of their conservation status and a lack of basic knowledge regarding their ecology and precise distribution.

Keywords: endemic species, Dalhousie, Edgbaston and Elizabeth Springs, conservation status, state, national and international legislation, threatened species

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Evolution in Isolation

At three spring complexes across Australia's arid interior, locally endemic fishes are extant. Although this fact may not appear exceptional at first glance – after all, they are springs, so there's water, so why wouldn't there be fish? – the complex ecology of Great Artesian Basin (GAB) springs illustrates a fascinating story about these unique fishes.

GAB springs are the exact opposite of islands. Just as an island is an isolated piece of land surrounded by water, a spring is an isolated area of water surrounded by land. Extending the island analogy to the biota of springs, there are similar and expected patterns. As Darwin famously observed, islands offer us tangible evidence of evolution in action: if a species is confined to an island, it may – over many generations – adapt and transform to make best use

of the available resources. Speciation – the formation of new and genetically distinct species – is the inevitable end-result. Biogeography is therefore littered with examples of creatures that evolved into new species in isolation on islands: Darwin's finches, the giant tortoises, Komodo dragons and the flightless dodos of Mauritius all demonstrate what happens when animals become marooned.

The rough equation – isolation plus time equals speciation – applies to springs in exactly the same way it does to islands. Isolation is relatively easy to understand: populations evolve differently in different areas. African elephants live on the savannah and have big ears and long tusks, whereas Asiatic elephants are smaller, live in the jungle and have small ears and smaller tusks. They have a common ancestor, but each went their own way.

Time is harder for us to understand, especially given our lifespans: it is difficult enough to envisage one thousand years of evolution, let alone 50,000, or 50 million. Yet in the context of GAB springs, we have to accept that: (a) the GAB springs were not *always* isolated oases surrounded by desert; and (b) the species we know now are a subset or a variation of what was there before. In other words, when diprotodons wallowed and disturbed the spring sediments as feral pigs and cattle do today, the fish fauna may have been slightly different. The entire fauna was likely very different several million years ago when crocodiles and lungfishes inhabited a permanent Lake Eyre (Byrne et al., 2008).

Freshwater fishes are most speciose in tropical areas where there are large rivers, multiple habitats and plenty of rainfall. As such, the Amazon and equatorial Africa are hotspots for diversity, and Australia is an extremely poor relation – arid Australia even more so (Kerezsy, 2017). The boom-bust cycle of Australia's inland ecosystems is driven by unpredictable flooding as opposed to a regular monsoon (Kingsford, 2017), and the paucity of freshwater fishes in the interior reflects the harshness of aquatic and surrounding terrestrial habitats: the interior is basically hard country for fish (Arthington & Balcombe, 2017).

Nevertheless, when the rains come and the rivers flow, plenty of itinerants end up making temporary homes in GAB springs. Glassfishes or perchlets (Ambassidae), colourful rainbowfishes (Melanotaeniidae) and hardyheads (Atherinidae) are all commonly encountered vagrants, as is the larger spangled perch (*Leiopotherapon unicolor*), a widespread carnivore with legendary colonisation ability and tolerances (to temperature, dissolved oxygen and other water quality parameters; Kerezsy et al., 2017). Members of these species appear to take their chances during the rare times when the desert is in flood and they can disperse widely (Kerezsy et al., 2013). If they are lucky, they may make it to a GAB spring – an area where water is likely to remain for far longer than the temporary habitat afforded by a sporadic flood. They may inhabit a spring for weeks, months or years, depending on whether enough individuals have colonised the particular spring and whether they can complete their life cycles within it. However, in most cases, opportunistic vagrants are there one year and gone the next. Returning to the island analogy, these are similar to the finches that may have visited certain islands in the Galapagos a few times, but lacked the adaptations to persist.

Endemic Fishes of GAB Springs

The narrow-range endemic fishes that today inhabit Dalhousie Springs (South Australia), the Pelican Creek Springs complex within the Barcaldine Springs supergroup, and the Elizabeth Springs complex within the Springvale supergroup (both in Queensland; Figure 1) are descended from various colonists of long ago. It's just that these species, rather than staying for months or years, survived and persisted for millennia, and became part of their localised ecosystems. Within this context, the opening sentence ("At three spring complexes across Australia's arid interior, locally endemic fish are extant") may become more intriguing, especially when it is considered that these species occur in harsh desert landscapes that could sometimes be considered the *least likely* places to offer aquatic habitats suitable to support viable fish populations.

Dalhousie Springs

At Dalhousie, in northern South Australia (Figure 1), the spring complex is surrounded by desert and gibber plain (Figure 2). Part of Witjira National Park, Dalhousie is most popular as either a starting- or end-point for tourists and adventurers to undertake four-wheel-drive crossings of the Simpson Desert. This means that in the tourist season

(roughly centred on the Australian winter, so May–September), the Park is busy, and on most afternoons tourists laze in the warm waters of one of the springs, swapping stories of dune-driving and breathtaking sunsets.

One of the endemic fish species from Dalhousie – the Dalhousie hardyhead (*Craterocephalus dalhousiensis*) – schools in the open water of the bigger springs, which can be longer than 100 m and deeper than 3 m (Glover, 1989; Figure 3). A hardyhead is a small, bullet-shaped fish that rarely exceeds 5 cm. They have distant relatives throughout Australia, including *C. eyresii* and *C. centralis* from catchments in the Lake Eyre Basin in South Australia and the Northern Territory, but are most closely related to *C. lentigenosus* from north-west Australia (Unmack & Dowling, 2010). The most likely evolutionary explanation for *C. dalhousiensis* is that an ancestral *Craterocephalus* – or perhaps one of the extant species – colonised Dalhousie in a flood, and then – gradually – evolved into a separate species in the isolated warm and constant spring habitat. As the tourists float and sip their beer in the springs at Dalhousie, it is hardyheads of the same name that peck morsels of food and detritus from their skin. Until recently it was considered that there were two species of hardyhead at Dalhousie – *C. dalhousiensis* and *C. gloveri* – however, fish biologists and geneticists acquainted with the springs and hardyheads now agree that only one species appears to be present (P. Unmack, M. Hammer, pers. comm.).

Figure 1. Map of Great Artesian Basin spring supergroups (within dotted lines) where spring complexes (black circles) at Dalhousie, Barcaldine (Pelican Creek complex) and Springvale (Elizabeth Springs complex) support endemic fish species.

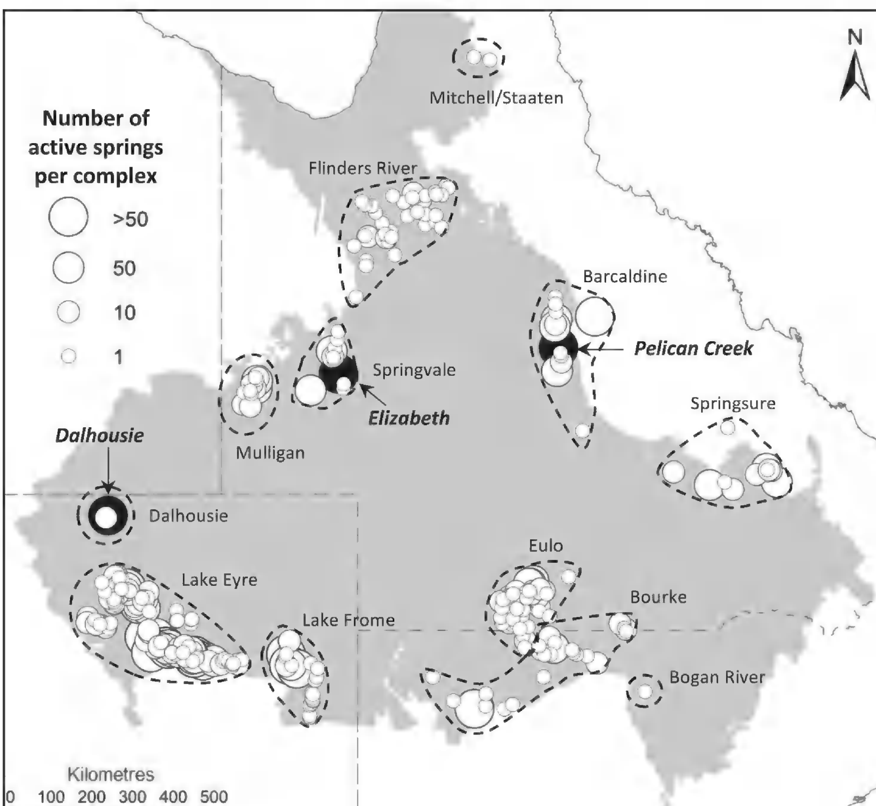

Figure 2. The desert landscape around Dalhousie (above) is in stark contrast to the springs (below). All photographs in this paper by the author.

Though not standard equipment on desert crossings, a mask and a snorkel are handy travel accessories at Dalhousie, for unlike the majority of waterways in central Australia, the GAB water in the springs is perfectly clear. When snorkelling, the first thing the swimmer will notice is just how common the hardyheads are; they're obviously perfectly adapted to their environment, where they feed on algae, micro-organisms and – opportunistically – on the detritus attached to visiting humans. Beneath the hardyhead, and busily shuffling across the substrate, is the second of the four fish species that occur only at Dalhousie Springs.

Dalhousie catfish (*Neosiluris gloveri*; Figure 3) belong to the catfish family Plotosidae, which are all eel-tailed (as opposed to fork-tailed). Their primary means of propulsion is the long fin/tail which extends beneath their body. Eel-tailed catfish of various species occur in most Australian catchments, and in the case of *Tandanus tandanus* from the Murray-Darling Basin, can grow to almost one metre long (Lintermans, 2007). The Dalhousie species, named after John Glover, a pioneering fish biologist from South Australia, is the smallest at less than 10 cm long, and also one of the few Australian fish species adapted to living in 40°C water (Glover, 1982). Again, other catfishes are known from catchments of the Lake Eyre Basin in central Australia, such as *Neosiluris hyrtlii* and *Porochilus argenteus* (Wager & Unmack, 2000), so the evolution of *N. gloveri* is likely due to an ancestral form becoming marooned in the hospitable habitat of these desert springs.

Figure 3. Dalhousie mogurnda (above) and Dalhousie catfish (below) are two of the four endemic fishes from the Dalhousie spring complex.

There are two main types of habitat at Dalhousie – the wide, deep, open pools, and the long, winding and often vegetation-congested ‘tails’. Spring tails at Dalhousie can be several kilometres long, and are often overgrown with *Phragmites* and *Typha* that can grow to several metres tall. The tails drain the water away from the pools where the main spring vents are situated, so they are far shallower (usually less than 50 cm deep).

The spring tails are the favoured habitat of *Mogurnda thermophila*, or the Dalhousie mogurnda (Figure 3). Mogurndas are commonly known as purple-spotted gudgeons and are attractive, bottom-dwelling species that have a comparatively wide range across Australia (Allen et al., 2002). The Dalhousie mogurnda, like the hardyhead and the catfish, has evolved to tolerate water up to and occasionally over 40°C. An ambush predator, they grow up to about 15 cm so are by far the largest endemic species occurring within the spring complex. A territorial species, it appears mogurndas wait in their own ‘space’ within the spring tails for food – such as shrimp, yabbies or other fish – to drift within striking range (pers. ob.).

Chlamydogobius gloveri – the Dalhousie goby – is the last of the Dalhousie endemics. Like its more widespread relation *C. eremius* (the desert goby; Rossini et al., 2018), this species is tolerant of extreme temperatures and salinity, and can even extract oxygen from the atmosphere using a pharyngeal organ (Thompson & Withers, 2002). Dalhousie gobies are poor swimmers and rarely grow larger than 5 cm. They are found throughout the Dalhousie Springs complex, including small springs and soaks where the other species do not occur.

Elizabeth Springs

North-east of South Australia and into the GAB springs of Queensland, the only fish species present at the Elizabeth Springs complex in the Springvale supergroup south-east of Boulia (Figure 1) is the Elizabeth Springs goby (*C. micropterus*; Larson 1995). In stark contrast to the extensive springs and tails of Dalhousie (that occur within approximately 70 km^2), all of the extant spring vents at Elizabeth Springs are situated within an area less than 500 × 500 metres (pers. ob.). Like its relatives in Dalhousie and throughout Central Australia, the Elizabeth Springs goby is benthic, tolerant and opportunistic. However, given that the Elizabeth Springs are shallow (mostly less than 5 cm deep) and small, Elizabeth Springs gobies persist within a far more restricted range than fishes in other spring complexes such as Dalhousie and the Pelican Creek complex at Edgbaston.

Pelican Creek Springs

On the eastern edge of the GAB, within the Barcaldine Springs supergroup, lies the Pelican Creek Springs complex. This complex is often referred to as ‘Edgbaston Springs’ because the vast majority of research to date has focused on the springs within Edgbaston Conservation Reserve. The springs at Edgbaston occur near the base of an escarpment, and contain the most diverse assemblages of invertebrates and plants (Figure 4; Fensham et al., 2011). There are up to 100 individual springs, but many are nothing more than damp areas.

In about 30 springs there are fish (Fairfax et al., 2007). Like Dalhousie and Elizabeth Springs, there is a resident goby – the Edgbaston goby, *C. squamigenus* (Figure 5) – and it is reasonable to assume, again, that speciation has been a direct consequence of isolation. Indeed, it seems likely that gobies are the most widespread endemic spring genus due to their ability to live in extremely shallow water: at Edgbaston, they frequently occur in water that is equivalent to (or less than) their body depth (of up to 1 cm; pers. ob.). Nevertheless, despite the apparent fortitude of the various gobies, the most curious inhabitant at Edgbaston – and possibly the most fascinating fish endemic in GAB springs – is the red-finned blue-eye (*Scaturiginichthys vermeilipinnis*; Figure 5).

Discovered by chance in 1990 by fish biologist Peter Unmack (Wager & Unmack, 2000), the red-finned blue-eye is the only representative of the Pseudomugilidae fish family in Central Australia, and its closest relative – *Pseudomugil tenellus*, the delicate blue-eye – is mostly associated with swamps in northern Australia and Papua New Guinea. The mysterious story of how red-finned blue-eye managed to colonise, evolve and persist in water that is frequently less than 3 cm deep and hotter than 40°C may never be known, but shortly after its discovery a far more pressing need was recognised, for it transpired that the fish was rapidly disappearing due to invasion of its unusual

habitat by the alien live-bearer eastern gambusia (*Gambusia holbrooki*; Fairfax et al., 2007; Kerezsy, 2009).

In 2008, Edgbaston Station, the *only* habitat for *S. vermeilipinnis*, was purchased by the not-for-profit conservation organisation Bush Heritage Australia, and a recovery program began to take shape. Trials of the piscicide Rotenone were undertaken in order to assess its usefulness as a tool for controlling eastern gambusia, and populations of red-finned blue-eye were relocated to safer areas (Kerezsy & Fensham, 2013). Luckily, by the time the naturally occurring populations had dwindled (there is only one population left today), several 'new' populations had been established (Radford et al., 2018). Although the future of this species remains precarious, with ongoing management hopefully it can persist.

Figure 4. The landscape around Edgbaston (above) and one of the larger springs (below).

Figure 5. Edgbaston goby (above) and male red-finned blue-eye (below).

Summary

There are narrow-range endemic fish species at three spring complexes in three supergroups across Australia's Great Artesian Basin. In the past there may have been many more, but currently there are seven endemic species: four at Dalhousie, two at Edgbaston, and one at Elizabeth Springs. It is important to note that at many spring complexes, there are simply no fish; this is possibly due to prehistoric extinctions, but in many cases the evidence of spring destruction by cattle, pigs and camels points to more recent extirpations. In other words, it's possible that there were more spring endemic fish species in comparatively recent history, but they disappeared before we knew they were there.

All fishes endemic to GAB springs are threatened by a broad suite of factors that endanger inland aquatic systems (Kingsford, 2017). However, these threats are neither limited to fishes of GAB springs nor to Australia's inland ecosystems. Worldwide, fishes from marginal habitats – especially in arid

areas – face similar threats from fragmentation of habitat, the imposition of alien or translocated species, extraction of ground and surface water, and climate change (Fagan et al., 2002; Unmack & Minckley, 2008; Kerezsy et al., 2017). The seriousness of such threats is amplified in Australia's GAB springs due to two main factors: the isolated and already-fragmented nature of the springs, and the comparatively large numbers of endemic species – of all groups – that live nowhere else. In other words, there are few buffers for spring endemics. If their habitat is destroyed, species extinction is the most likely outcome.

The endemic fishes of Australia's GAB springs are all functionally endangered due to their small ranges and small populations; however, their formal conservation status varies widely between state, national and international legislation and/or lists (Table 1). Persisting as they do in such unique and specialised habitats, the study of these GAB fish species – and all GAB springs endemics – can reveal much about evolution, speciation and resilience. It is therefore imperative that we respect and conserve them and their unusual habitats.

Acknowledgements

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Table 1. The status of narrow-range endemic fishes from Australia's Great Artesian Basin springs under state and Commonwealth legislation, and their international status on the IUCN Red List of Threatened Species.

Species	Common name	State legislation	Commonwealth legislation	IUCN Red List
South Australian species				
Craterocephalus dalhousiensis	Dalhousie hardyhead	All four Dalhousie species are considered protected in South Australia as they occur within a national park; however, they are not listed under South Australian legislation (M. Hammer, pers. comm.).	All four Dalhousie species are not individually listed.*	Critically endangered (Whiterod et al., 2019a)
Neosiluris gloveri	Dalhousie catfish			Critically endangered (Whiterod et al., 2019b)
Chlamydogobius gloveri	Dalhousie goby			Critically endangered (Hammer et al., 2019)
Mogurnda thermophila	Dalhousie mogurnda			Critically endangered (Unmack et al., 2019)
Queensland species				
Chlamydogobius micropterus	Elizabeth Springs goby	Endangered (NCA, 1992)	Endangered (EPBC Act, 1999a)*	Vulnerable (Kerezsy et al., 2019)
Chlamydogobius squamigenus	Edgbaston goby	Endangered (NCA, 1992)	Vulnerable (EPBC Act, 1999b)*	Critically endangered (Kerezsy et al., 2019a)
Scaturiginichthys vermeilipinnis	Red-finned blue-eye	Endangered (NCA, 1992)	Endangered (EPBC Act, 1999a)*	Critically endangered (Kerezsy et al., 2019b)

*The community of native species dependent upon natural discharge of groundwater from the Great Artesian Basin is listed as an endangered ecological community (EPBC Act, 1999c) in addition to individually listed species.

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Author Profile

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The Distribution of the Endangered Fish Edgbaston Goby, *Chlamydogobius squamigenus*, and Recommendations for Management

Adam Kerezsy[1]

Abstract

Surveys conducted in bore drains in the Aramac district of central-western Queensland found that species of both plants and animals endemic to Great Artesian Basin springs are capable of colonising and surviving in these artificial environments. In particular, the discovery of an endangered fish, Edgbaston goby (*Chlamydogobius squamigenus*) in bore drains approximately 20 km from its native natural spring habitat suggests that spring-dependent species are likely to seek new habitats when migration pathways are open during flooding. Managing the declining populations of spring endemics, such as Edgbaston goby, could occur through maintaining populations in artificial springs or wetlands where the invasive eastern gambusia (*Gambusia holbrooki*), which is thought to competitively exclude small native fishes, can either be excluded or removed.

Keywords: Edgbaston goby, bore drains, endangered species, Edgbaston Springs, Great Artesian Basin springs

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Introduction

Great Artesian Basin (GAB) springs are considered the most ecologically important inland waters in Australia and provide habitat for a number of endemic species from diverse plant and animal groups (Fensham et al., 2011). Great Artesian Basin springs are generally concentrated around the margins of the basin, and examples include the Mulligan supergroup on the eastern edge of the Simpson Desert in Queensland, and the Dalhousie supergroup in northern South Australia. Although many GAB spring complexes can be considered compromised due to extended exploitation and concomitant destruction due to their use as water points for grazing, the springs at Edgbaston, located in the Barcaldine supergroup in central-western Queensland, are an exception. Comprising approximately 100 individual spring vents, Edgbaston is the most diverse spring complex in the GAB and was purchased in 2008 by the conservation not-for-profit Bush Heritage Australia.

Since 2009, the endangered fish species red-finned blue-eye (*Scaturiginichthys vermelipinnis*) has commanded the majority of attention at Edgbaston due to its heightened extinction risk (Kerezsy & Fensham, 2013; Radford et al., 2018). Although this has resulted in a better survival outlook for this species, work on the other endemic fish, Edgbaston goby (*Chlamydogobius squamigenus*) has generally not occurred – and certainly not to the same degree – until recently. Similarly, general work on the presence/absence of invertebrates, though ongoing for some time (Ponder et al., 2010), has only recently considered ecological themes (Rossini et al., 2017).

Gobies are a widespread and speciose fish family worldwide, but comparatively few species are native to Australia, and even fewer live in the arid and semi-arid interior of the country. Indeed, the only gobies known from the Lake Eyre Basin are the Edgbaston goby and its related species at the Elizabeth Springs complex (Springvale supergroup)

in the Diamantina catchment in western Queensland (*Chlamydogobius micropterus*), at Dalhousie Springs in northern South Australia (*Chlamydogobius dalhousiensis*), in the Finke River in the Northern Territory (*Chlamydogobius japalpa*), and in the southern Lake Eyre Basin (*Chlamydogobius eremius*), as well as the larger species golden goby (*Glossogobius aureus*), which is known from riverine sites in the Mulligan, Georgina and Diamantina catchments in far-western Queensland (Wager & Unmack, 2000; Kerezsy et al., 2013; Kerezsy, 2017).

Speciation within the *Chlamydogobius* genus is likely to be a result of isolation due to Australia's drying climate over a long time period: as permanent water in the arid zone became scarcer, the gobies were probably forced to retreat to spring complexes (at Edgbaston, Elizabeth Springs and Dalhousie) and isolated water sources in the Finke and southern Lake Eyre regions. These small 'desert' gobies possess adaptations that enable them to live in oxygen-poor and shallow water, such as a pharyngeal organ that extracts oxygen from the air (Thompson & Withers, 2002). They also exhibit parental care of their young, as the male guards and fans (or aerates) clutches of fertilised eggs until they hatch (Allen et al., 2002).

Edgbaston goby is a benthic species that grows to a maximum length of 5–6 cm (Allen et al., 2002). The species is listed as endangered under the *Nature Conservation Act 1992* (Parliament of Queensland, 1992), vulnerable under the *Environment Protection and Biodiversity Conservation Act 1999* (Parliament of Australia, 1999) and critically endangered by the IUCN (Kerezsy et al., 2019). Populations of Edgbaston goby were found in eight springs at Edgbaston in 1994 (Wager, 1994), and at nine in 2009 (Kerezsy, 2009). A population previously recorded from a bore drain at Crossmoor Station can be considered extinct, as this bore has been capped (Russell Fairfax, pers. comm.). Populations of Edgbaston goby have also been recorded in a spring environment at Myross (which adjoins Edgbaston; Rod Fensham, pers. comm.). It is important to note that as Edgbaston goby is a bottom-dwelling species, the term 'population' may only refer to a small number of individuals (<50) that live in small colonies in isolated springs.

This paper presents the results from biological surveys of bore drains and springs in the Aramac district conducted in mid-2014. The objectives were to more accurately establish the current distribution of Edgbaston goby, to audit extant aquatic fauna and flora, and to inform future management of this endangered species and other spring endemics. Bore drains were included in the surveys as they are similar to springs and represent areas of permanent water in an otherwise arid environment. In many cases they have been present within the GAB landscape for over 100 years, and it was considered possible that spring endemics (such as the Edgbaston goby) may have colonised such habitats during periods of flooding (for example 1974–1975 and 2010–2011). The paper concludes with discussions of the future management of Edgbaston goby and other spring endemics, and the role that bore drains could possibly play in sustaining populations of range-limited threatened species and communities.

Materials and Methods

Study Area

Bore drains were identified and a list of properties and landowners was provided by the natural resource management group Desert Channels Queensland. Landowners were contacted in order to arrange a convenient time for the surveys to be conducted. Surveys were undertaken on a total of 10 properties in the Aramac district including Glenaras, Acacia Downs, Merino Downs, Stainburn Downs, Ravenswood, Stagmount, Myross, Pendine, Hathaway and Edgbaston. Multiple sites were chosen on properties where more than one drain or spring was present (such as Stagmount, Ravenswood, Myross and Edgbaston).

During an earlier fish survey at Edgbaston, over 90 springs were sampled (Kerezsy, 2009), and more springs have been found in the interim (A. Kerezsy, R. Rossini, R. Fensham, P. Kern, pers. ob.). However, approximately half of the known spring vents at Edgbaston do not discharge enough water to provide habitat for fish, and these were omitted from the current survey. Springs/sites used during the Edgbaston survey included all springs where fish (of any species) have been recorded previously (Wager, 1994; Fairfax et al., 2007; Kerezsy, 2009), as well as shallow springs (<2 cm deep) that could be considered potential habitat for Edgbaston goby. Fifty-four springs were sampled at Edgbaston

during the survey. Surveys took place from 14–24 August 2014.

Physical Characteristics and Water Quality

At each site, a snapshot of environmental conditions was made by recording physical characteristics such as the depth, width and length of each drain and spring (where possible), as well as the soil type and surrounding terrestrial vegetation. Similarly, a singular recording of water quality parameters such as pH, electrical conductivity (a surrogate for salinity), dissolved oxygen and temperature was made using a Eutech multimeter at each site, and turbidity was measured using a Secchi disc. Although all bores were sampled along their drains – the section that meanders through the landscape – additional water quality readings were taken in some instances (Glenaras, Acacia Downs and Ravenswood) at or close to the bore 'heads' (i.e. the location of the bores, and where the water first enters the above-ground landscape).

Biological Sampling

A combination of methods was used in order to maximise the chances of sampling the greatest diversity of biota; however, in the shallow spring environments active searching was the only viable method, as the depth of each spring rarely exceeded 5 cm. Active searching – slowly walking through the spring and recording observations – was undertaken at each site for a minimum period of 30 minutes in order to identify plants and any animals that were easily observed (such as red-finned blue-eye, Edgbaston goby, the alien fish eastern gambusia (*Gambusia holbrooki*), yabbies (*Cherax destructor*) and cane toads (*Rhinella marina*)). Fish and invertebrates were sampled by random dip-netting for the same time period using a 250 μm mesh net, and included both longitudinal and transverse netting of each bore-drain channel. Where depth allowed, cylindrical plastic bait traps (30 cm long and 10 cm in diameter with a 2 cm entry hole) were baited with dog food and set for 2 hours. In deeper water, mesh bait traps (40 cm × 20 cm with a 3 cm entry hole made from 2 mm mesh) were also used. At Ravenswood and Edgbaston, spotlighting was used as a follow-up method to confirm the presence of Edgbaston goby. At Edgbaston, plant and invertebrate sampling was omitted due to the number of sites (54), the diversity of species, and the existing literature pertaining to the diversity of these groups (Ponder et al., 2010; Fensham et al., 2011; Rossini et al., 2017).

All invertebrate and fish sampling was carried out under General Fisheries Permits issued by the Queensland Department of Primary Industries (89212 and 166743) and an animal ethics agreement (CA2010/02/415). Any sampled native fish were returned to the water at the point of capture, and any alien fish that were collected (as opposed to observed) were euthanised using approved techniques.

Results

Physical Characteristics and Water Quality

The majority of the sampled bore drains (those on Glenaras, Acacia Downs, Merino Downs, Stainburn Downs, Pendine, Hathaway and Myross 1) were very similar: long, meandering channels in black, cracking clays that were generally between 10 and 100 cm wide and less than 15 cm deep. As an example, the drain at Merino Downs was 8 km long but less than 1 m wide (Figure 1). In general, the drains have been configured with a view to watering more than one paddock: at Glenaras, four drains flow in different directions from the bore head, whereas at Stainburn Downs 'tributary' channels run at right angles to the main channel. The dominant terrestrial vegetation at the sites mentioned above was Mitchell grass (*Astrebla* spp.) with an overstorey of mimosa (*Acacia farnesiana*).

The bore drains at Ravenswood differed from the main group, as they occurred in sandy country and, rather than running for many kilometres, they terminate in wetlands. Similarly, at Stagmount 1 (Figure 2), the head of the bore drained straight to an extensive wetland (approximately 2 km long and up to 100 m wide) before reverting to the more typical drains discussed above. At Stagmount 2, the drain ran through a canopy of black gidgee (*Acacia argyrodendron*). At Myross 2, the spring drain (which was generally wider than 1 m) originated in a large spring (approximately 100 × 30 m and up to 1.5 m deep), where the surrounding vegetation is comprised of spinifex and *Melaleuca*: this vegetation is typical of springs in the area, as is the surrounding rock (travertine).

Figure 1. The drain at Merino Downs north of Aramac is a typical example of the majority of bore drains in the district.

Figure 2. The bore drain at Stagmount, showing a much larger diversity of aquatic vegetation (which included spring endemics). Drains at both Stagmount and Ravenswood were notable for this increased diversity.

Water quality parameters at all sites fell within expected ranges for water from the GAB in central western Queensland, with neutral to alkaline pH values (7.09–8.80) and slightly salty conductivity readings (381–1085 μS/cm; Table 1). Dissolved oxygen (0.91–8.09 mg/L) and temperature (10.5–58.1°C) were far more variable (as expected) depending on proximity to the bore head and time of day. In general, drains reverted to ambient temperatures after a distance of approximately two kilometres from the bore head. The bore with the highest temperature was at Acacia Downs, and the bore with the lowest temperature was at Ravenswood (Table 1).

At Edgbaston, water quality parameters fell within expected ranges at all sites (Appendix 1). Temperature varied according to the time of day each spring was sampled: water temperatures higher than 30°C were recorded between 11 am and 4 pm, whereas lower water temperatures were recorded at sites sampled in the mornings and afternoons (Appendix 1). Dissolved oxygen varied according to distance from the spring vent: low dissolved oxygen (<1 mg/L) was recorded close to spring vents, whereas high dissolved oxygen was recorded in the larger pooled areas (Appendix 1).

Biological Survey Results

Across all 17 sites (excluding Edgbaston), biota sampled in mid-2014 included five species of fish, two crustaceans (yabbies and shrimp), various insects and both generic aquatic plants (i.e. species that could be expected to occur in inland Australian waters), and endemic plant species only known from Great Artesian Basin springs (Table 2).

Table 1. Water quality at bore drains in the Aramac district in August 2014. G = Glenaras, AD = Acacia Downs, MD = Merino Downs, SB = Stainburn Downs, R = Ravenswood, S = Stagmount, P = Pendine, H = Hathaway, and M = Myross. All readings (and samples) were taken from the tails of bore drains unless stipulated.

Site	pH	Conductivity (μS/cm)	DO (mg/L)	DO (% saturation)	Temperature (°C)	Turbidity (cm)
G	8.28	1075	3.04	41.9	34	Clear
G head	7.79	804	0.91	12.8	47.7	Clear
AD	7.82	1085	8.09	75.4	10.5	3
AD 100 m from head	8.6	1034	5.65	73	45.1	Clear
AD head	7.75	1064	1.43	26.2	58.1	Clear
MD	8.09	710	6.04	68.7	16.7	5
SB 1	6.91	451	7.65	71.4	10.5	5
SB 2	7.2	701	1.8	18	12.3	3
SB 3	7.16	941	7.38	77.3	15.6	4
R	8.8	398	6.03	80.5	29.2	Clear
R head pool	7.39	381	3.3	47.3	32.8	Clear
R head	7.44	382	1.49	20.1	32.7	Clear
S1	7.38	609	2.8	34.2	30.3	Clear
S2 head	7.09	687	2.37	32.6	43.1	Clear
P	7.95	542	5.2	57.3	16.8	6
H	7.39	543	2.48	33.1	26.3	5
M	7.42	483	7.73	96	25.7	4

Table 2. Aquatic biota sampled in bore drains and one spring drain in the Aramac district in August 2014. G = Glenaras, AD = Acacia Downs, MD = Merino Downs, SB = Stainburn Downs, R = Ravenswood, S = Stagmount, P = Pendine, H = Hathaway and M = Myross.

	G	AD	MD	SD1	SD2	SD3	R1	R2	S1	S2	P	H	M1	M2
Fish														
Gambusia*														
Edgbaston goby**														
Spangled perch														
Glassfish														
Rainbowfish														
Crustaceans														
Shrimp (Atyidae)														
Yabby														
Insects														
Dragonfly larvae														
Damselfly larvae														
Beetles														
Corixids														
Other fauna														
Cane toad*														
Plants														
General aquatic														
Spring endemic**														

Note that the Myross 2 site is a spring drain (as opposed to a bore drain), *alien species, **endangered species/ecological community.

Gambusia was the most commonly collected fish species and was found at all sites (Table 2).

Outside Edgbaston, the endangered Edgbaston goby was found at Myross 2 (which was expected, given this is a spring drain very close to Edgbaston, where the species is widespread) and, unexpectedly, in a bore drain at Ravenswood (Table 2; Figure 3). This represents a significant range extension for this species. The site at Ravenswood is approximately 20 km south of the closest Edgbaston/Myross population, and it is speculated that gobies from Edgbaston/Myross likely migrated to Ravenswood during overland flooding (Figure 3). Spangled perch, *Leiopotherapon unicolor*, is a colonising species and has been found in remote desert environments following sporadic rainfall (Kerezsy et al., 2013), so the presence of this species at two sites, Myross 2 and Ravenswood, during this survey is unremarkable. Other landholders also mentioned seeing this species in their drains at various times (C. Dyer, Stainburn Downs, and P. McAuliffe, Stagmount, pers. comms). Finally, two riverine species, desert rainbowfish (*Melanotaenia splendida tatei*) and glassfish (*Ambassis* sp.), were also recorded at Myross 2. It seems most likely that these species colonised Myross 2 from the nearby (and ephemeral) Pelican Creek during a flood or wet period (Table 2). Although a species of hardyhead (*Craterocephalus* sp.) has previously been recorded at Myross 2, none were collected on this occasion.

Figure 3. The current distribution of Edgbaston goby (indicated by yellow stars) includes the cluster of populations in and around springs at Edgbaston, and the newly discovered Ravenswood population approximately 20 km south (map courtesy of J. Silcock).

The survey results suggest that a variety of native crustaceans and insects utilise the bore drains in the Aramac district (Table 2); however, it is notable that the vast majority (for example yabbies, shrimp, dragonfly nymphs and corixids) are either capable aquatic colonisers or flying insects that utilise available water for breeding and when immature. Undoubtedly, the low detection rate for cane toads during the survey was a function of the time of year (14–24 August 2014), as most landholders commented that during warmer months cane toads were common in their bore drains.

Common aquatic plants such as *Azolla* and/or *Cyperus*, *Nardoo*, *Monochoria*, *Typha* and *Phragmites* were present throughout the sites, and the terrestrial weed Noogoora Burr (*Xanthium occidentale*) was present on both Stainburn and Merino Downs (Table 2). Stands of *Typha* and *Phragmites* were most common (and densest) at Stagmount 1 and Ravenswood (Figure 3). Spring vegetation, such as *Myriophyllum artesium* and *Eriocaulon carsonii*, was found (as expected) at Myross 2. However, both species were also found at Stagmount 1, and *M. artesium* was also found at Ravenswood (Table 2). These populations are significant, as they demonstrate that plant species endemic to springs may also colonise artificial waters.

At Edgbaston, fish were found in 39 of the 54 sampled springs in mid-2014. Gambusia was the most widespread fish and occurred in all spring groups (NW, E, SE, SWN, SW, NE; see Kerezsy & Fensham, 2013 for further explanation) and in a total of 28 springs (Appendix 2). Red-finned blue-eye was recorded from nine springs in the NW and E spring groups, comprising natural and relocated populations (Appendix 2; Kerezsy & Fensham, 2013). Edgbaston goby was recorded from nine springs in the NW and E spring groups (Appendix 2). At three springs Edgbaston goby was the only fish present, and at a further three springs Edgbaston goby co-occurred with red-finned blue-eye (Appendix 2). Edgbaston goby co-occurred with both red-finned blue-eye and gambusia at two springs (Appendix 2).

Discussion

The ‘rediscovery’ of populations of endangered species is not a common occurrence. Undoubtedly the most high-profile and controversial instance of this occurring in recent Australian history pertains to the night parrot (*Pezoporus occidentalis*) in Australia’s arid inland (Ohlsen et al., 2016). Although the range extension for the endangered Edgbaston goby revealed by this study is easily explained by the geographic proximity of the ‘new’ population at Ravenswood to the likely source populations at Edgbaston and Myross, the result is important for two reasons. First, the Ravenswood population does not occur in a GAB spring, but in a bore drain; and second, the existence of the Ravenswood population demonstrates that this species can – at least under certain circumstances – survive (as a viable population) despite the presence of gambusia. These observations suggest that Edgbaston goby may be a hardy species (especially compared with red-finned blue-eye) and that management of such an endangered species could involve a suite of unconventional methods, such as retaining populations in artificial environments that utilise GAB water but otherwise are physically different from GAB springs.

All artificial water points in central-western Queensland are the result of Anglo-European colonisation. As bore drains often provide permanent water in an otherwise arid environment, they have undoubtedly altered the local and regional ecosystems in which they occur (Fensham & Fairfax, 2008). Although the bores and their drains have provided water to support stock grazing and to sustain isolated communities and homesteads, their presence – in essence the fact that they provide a reliable water supply – has also facilitated an expansion in native macropod numbers as well as similar increases in introduced herbivores (such as goats and camels), omnivores (pigs), and both native and introduced carnivores (dingoes, dogs, cats and foxes; James et al., 1999). The Great Artesian Basin Sustainability Initiative (GABSI) has been effective in reversing some of these negative impacts, and through capping and piping bores has conserved water, restored groundwater pressure and reduced the number of artificial water points. Nevertheless, the current survey provides evidence that these artificial environments also have the potential to support aquatic biota previously thought to be endemic spring specialists. Additional surveys of bore drains throughout the GAB could reveal further sites of significance for the conservation of spring biota.

At local scales (within individual bores and their drains), it is also possible to discern successional trends, and these patterns of colonisation are obviously related to the proximity of bore drains to source populations of aquatic biota. In ‘basic’ bore drains that were somewhat isolated from springs, such as those on Merino Downs and Stainburn Downs, the colonising biota could be described as ‘generalist’ or ‘ubiquitous’. For example, the insects were all corixids, there were shrimp and yabbies, the fish were (all) gambusia, and there had been colonisation by general aquatic vegetation. However, bore drains closer to springs, such as Ravenswood and Stagmount, also included endemic spring vegetation, a greater diversity of invertebrates and – at Ravenswood – Edgbaston goby. These results suggest that maintaining populations of spring endemics is certainly possible in artificial/created wetlands that utilise water from the GAB, and given the endangered status of these communities (and many of the species within them) this may be a sensible management option.

Conserving endangered species in managed habitats – particularly in arid areas – is developing into a viable conservation tool. In South Australia, the populations of at least two genera of native rodents increased following the completion of a predator-proof fence at the Arid Recovery site near Roxby Downs (Moseby et al., 2009). In North America, translocation has been advocated and practised for far longer, and this has included Cyprinodontid spring fishes (i.e. pupfishes) that face similar challenges to Australia’s spring endemics (Minckley, 1995; Keepers et al., 2018). There is certainly a precedent for actively managing the population of Edgbaston goby in ‘safe’ habitats (such as predator/competition-free springs), as the relocation of red-finned blue-eye has been mostly successful in the same area (Kerezsy & Fensham, 2013; Appendix 2). Creating artificial spring environments appears to be slightly more difficult, or at least subject to more challenges (Karam et al., 2012); however, the creation of ‘artificial’ springs on-site at Edgbaston in order to conserve the red-finned blue-eye is a local example that appears to be achieving early success (P. Kern, pers. comm.).

Unfortunately, the great majority of bore drains in central-western Queensland (and all of the drains sampled during this study) have been colonised by gambusia, thus rendering them unsuitable for the recovery of endangered native fish. The impacts of gambusia on other small-bodied fish include egg predation, direct competition for resources, and territorial behaviour (Howe et al., 1997; Ivantsoff & Aarn, 1999), while their life history advantages include giving birth to live young, as well as tolerance of high temperatures and poor water quality (Pyke, 2008). Springs and bore drains in central Australia – again unfortunately – provide perfect habitat for this adaptable invasive species, so creating areas that are (and can be kept) free from gambusia should be a priority for the conservation of endemic fishes from GAB springs (Kerezsy & Fensham, 2013). Ongoing monitoring of the Ravenswood population of Edgbaston goby, as well as the populations at Edgbaston that currently co-habit with gambusia, is also necessary in order to better ascertain the linkage (if there is one) between gambusia presence/abundance and Edgbaston goby decline. Additionally, given that there is already low genetic diversity within extant populations of Edgbaston goby (Faulks et al., 2016) and that the Ravenswood population is not genetically distinct from those at Edgbaston (P. Unmack, pers. comm.), preservation of the species could be well served by the establishment of ‘insurance’ populations in artificial springs and wetlands that are inaccessible to gambusia.

The discovery of a previously unknown population of an endangered species such as Edgbaston goby should provide valuable lessons to those charged with managing Australia’s endangered species. It demonstrates, firstly, that effort must be directed towards accurately establishing the distribution of such species, and that this can only be achieved through surveys of likely habitats. Similarly, effort must be directed towards identifying and mapping habitat areas that may be suitable for maintaining populations of endangered species, even if these areas have artificial origins, such as bore drains. Last, this survey demonstrates that endangered species, despite being disadvantaged by small populations, limited suitable habitats and the imposition of invasive species, are sometimes capable of persisting in less-than-perfect circumstances. To enable such species to endure, and to improve these circumstances as much as possible, should therefore be the aim of all endangered species programs and recovery plans.

Appendix 1

Water quality parameters recorded from all springs sampled at Edgbaston in October 2014

Spring	pH	Conductivity (μS/cm)	Dissolved oxygen (% saturation)	Dissolved oxygen (mg/L)	Temperature (°C)
NW30	8.22	457.4	43.2	2.95	27.5
NW70	7.70	801.7	14	1.23	27.2
NW80	7.90	878.1	17.8	1.48	26.9
NW90n	7.66	911.2	48.9	3.5	29.5
NW90s	8.01	856.1	75.5	4.64	28.7
NW72	7.93	982.8	56.7	4.28	24.1
E502	7.93	845.8	60.1	4.54	29.9
NW40	8.07	785.8	24.8	1.31	27.3
NW50	8.85	826.6	70.6	5.27	27.1
NW60	8.11	1024	87.5	6.69	27.5
NW20	7.95	927.2	45.2	3.70	27.9
NW10	8.59	925.4	74.7	5.29	28.5
NW100	8.49	904.7	66.1	4.41	33
E501	8.6	700	90.9	6.23	32.6
E524	9.2	698.5	88.2	6.89	32.2
E505	8.17	1164	72.3	6.13	34.2
Smithy's	8.95	1060	82.3	5.42	34.7
E504	8.48	846.2	47.5	3.41	31.6
New Big	7.84	860.7	65.8	4.48	29.5
E518	9.08	966.6	102.4	7.34	33.2
E515	9.44	1107	78.3	5.31	35
E508	8.14	655.3	43.6	3.22	32.7
E509	9.5	827.2	83.9	5.61	30.4
E1	8.68	896.4	71.4	4.58	32.5
Fence	8.49	655.4	54.5	3.39	30.5
2011#1	8.4	884.8	73.3	5.05	31.9
2011#2	9.89	1172	120.4	9.05	32.2
NE95	7.53	795.7	13.4	1.29	22.1
NE75	8.07	804.3	27.2	1.3	21.6
NE72	8.05	875.4	13	1.12	22.5
NE08	8.32	646.9	28.7	1.05	28.9
NE07	8.45	1538	10.1	0.9	22.5
NE10	8.82	957.6	41.8	2.6	22.1
NE01	8.19	1373	29.8	2.45	22.5
NE03	8.19	1218	26.3	1.91	25.1
NE20	7.79	795.5	7.4	0.74	27.3
NE30	7.85	881.2	68	4.95	31.9
NE40	7.76	769.6	11.5	0.96	26.8
NE50	8.19	958.1	78.2	5.93	31.3
NE60	8.29	887.8	59.7	4.67	30.7
SWN10	9.4	941.5	81.3	5.99	32.3
SWN20	10.10	1225	149.2	10.73	34.4
SWN30	8.08	880.9	97	6.74	32.8
SW40	8.65	1686	18.7	0.51	36.1
SW42	9.34	742.1	81.1	5.67	32
SW50	9.52	977.6	72.5	5.00	30.3
SW65	8.94	640.3	85.6	5.94	33.9
SW60	8.57	552.4	76.5	4.09	31.9
SW70	9.6	579.6	68.2	4.81	30.2
E523	8.09	699	41.8	3.28	27.8

Appendix 2

Fish presence/absence at 54 springs at Edgbaston in October 2014. Filled areas indicate the species was present at the site. Relocation establishment dates are given for relocated red-finned blue-eye populations and are explained in more detail in Kerezsy & Fensham (2013).

Spring	Edgbaston goby	Red-finned blue-eye	Gambusia
NW30			
NW70			
NW80		Relocated 2014	
NW90n			
NW90s			
NW72		Relocated 2009	
NW40			
NW50			
NW60			
NW10			
NW20			
NW100			
E502			
E501		Relocated 2009 and 2011	
E524		Relocated 2011	
E505			
Smithy's			
E504		Relocated 2012	
New Big			
E518		Relocated 2011	
E515			
E508			
E509		Relocated 2012	
E1			
Fence			
2011#1			
2011#2			
E523			
SWN10			
SWN20			
SWN30			
SW40			
SW42			
SW50			
SW60			
SW65			
SW70			
SE40			
SE50			
SE60			
SE10			
NE95			
NE75			
NE72			
NE08			
NE07			
NE10			
NE01			
NE03			
NE20			
NE30			
NE40			
NE50			
NE60			

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Do Cane Toads (*Rhinella marina*) Impact Desert Spring Ecosystems?

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Abstract

Since their introduction in 1935, cane toads (*Rhinella marina* (Linnaeus, 1758)) have established and spread throughout north and north-eastern Australia. Cane toad impacts on terrestrial ecosystems are well documented, but impacts on aquatic ecosystems are less well known. We investigated the diet of cane toads collected from warm Great Artesian Basin-fed springs on Edgbaston Reserve in central Queensland, Australia. A higher proportion of aquatic invertebrates to terrestrial invertebrates was found amongst their alimentary canal contents. Aquatic taxa consumed included molluscs (Gastropoda), insects (Coleoptera) and crustaceans (Amphipoda). Given this diet, the presence of cane toads at Edgbaston Springs, and the high endemicity of the aquatic biota of these springs, we conclude that *R. marina* present a threat to the conservation of desert spring ecosystems.

Keywords: Queensland, Edgbaston, spring, Great Artesian Basin, aquatic invertebrates, pest, invasive species

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Introduction

The cane toad *Rhinella marina* (formerly *Bufo marinus* (Linnaeus, 1758)) is an amphibian native to Central and South America belonging to the family Bufonidae. This species was introduced to coastal Queensland in 1935 as an ultimately unsuccessful biological control agent for sugar cane pests (Freeland, 1984; Lever, 2001). Since then, it has spread widely throughout north and north-eastern Australia (Sutherst et al., 1995; Urban et al., 2007), causing significant negative impacts on Australian ecosystems (Phillips et al., 2003; Shine, 2010).

Cane toads are opportunistic generalist feeders (Zug & Zug, 1979; Reed et al., 2007; Heise-Pavolv & Longway, 2011) and are able to withstand a wide range of climatic conditions (Lever, 2001; Urban et al., 2007). Their resilient nature in combination with the high vagility of adults has enabled the species to expand its range to now occupy over 1.2 million km^2 of Australia. They are predominantly found in tropical and subtropical areas including much of Queensland. There is potential for this range to further expand to over 2 million km^2 across all mainland states (Urban et al., 2007).

Like many introduced species, cane toad populations in Australia are exposed to few of the predators, parasites and pathogens present in their native range (Speare, 1990), reducing the impacts of predation and disease on population size and life expectancy. Furthermore, all life stages of the cane toad (from egg to adult) contain toxins such as bufotoxins and bufogenins, which deter predators (Alford et al., 1995). Having not historically encountered these toxins, Australian fauna lack behavioural or physiological mechanisms to alleviate either exposure or the toxic responses to exposure (Lever, 2001).

While the ingestion of cane toad toxins threatens a variety of Australian fauna (Doody et al., 2009; Phillips et al., 2003; Shine, 2010), the direct consumption of native fauna by the cane toads is

also a threat. Cane toads are indiscriminate feeders able to form large populations, which can consume large quantities of invertebrates (Zug & Zug, 1979; Freeland et al., 1986; Shine, 2010; Heise-Pavlov & Longway, 2011).

The adult cane toad diet has been studied extensively, with alimentary canal contents dominated by terrestrial invertebrate prey (e.g. beetles, termites and ants) (Freeland, 1984; Strüssmann et al., 1984; Freeland et al., 1986; Reed et al., 2007; see also Shine, 2010). Current evidence is lacking regarding adult cane toads specifically targeting aquatic invertebrates, with no previous research into the diet of cane toads inhabiting springs. There are, however, documented cases of aquatic macroinvertebrates, such as beetles from the families Hydrophilidae and Dytiscidae, being consumed by cane toads (Hinckley, 1963), indicating this species is a potential threat to aquatic ecosystems. Aquatic predators are further threatened by cane toads as the consumption of cane toad eggs and tadpoles can be fatal due to their toxicity (Crossland & Alford, 1998; Somaweera & Shine, 2012).

R. marina was recently identified as a potential threat to the unique Great Artesian Basin (GAB) spring wetland communities in Queensland (Fensham et al., 2010), including the Pelican Creek spring complex, partially located on Edgbaston Reserve. The spring wetlands within Edgbaston Reserve represent a permanent source of water in a semi-arid region, and their long isolation has resulted in a diverse and endemic GAB spring community of fish, aquatic plants and aquatic macroinvertebrates (Ponder & Clarke, 1990; Wager & Unmack, 2000; Fensham et al., 2010). All GAB spring communities are listed as Endangered under the Australian *Environment Protection and Biodiversity Conservation Act 1999* (the EPBC Act), with several endemic species also individually listed as endangered or vulnerable (of particular note are the red-finned blue-eye (*Scaturiginichthys vermeilipinnis*) and the Elizabeth Springs goby (*Chlamydogobius micropterus*)). As available sources of water in often arid or semi-arid regions, GAB springs inherently attract a range of fauna including introduced species such as feral pigs and cane toads (Fensham et al., 2010; Fensham et al., 2011). While the permanency of surface water in springs provides opportunity for cane toads to persist in this dry landscape, the underlying processes and mechanisms of their potential impacts are yet to be quantified.

This paper presents an initial investigation of the adult cane toad diet within a GAB spring wetland at Edgbaston Reserve in central Queensland. It was hypothesised that given the opportunistic feeding habits of adult cane toads and the limited surface water in these regions, adult toads will be consuming aquatic invertebrates from GAB springs. If so, this poses a threat to the endangered GAB spring community within Edgbaston Reserve, in particular the rare and endemic aquatic invertebrates.

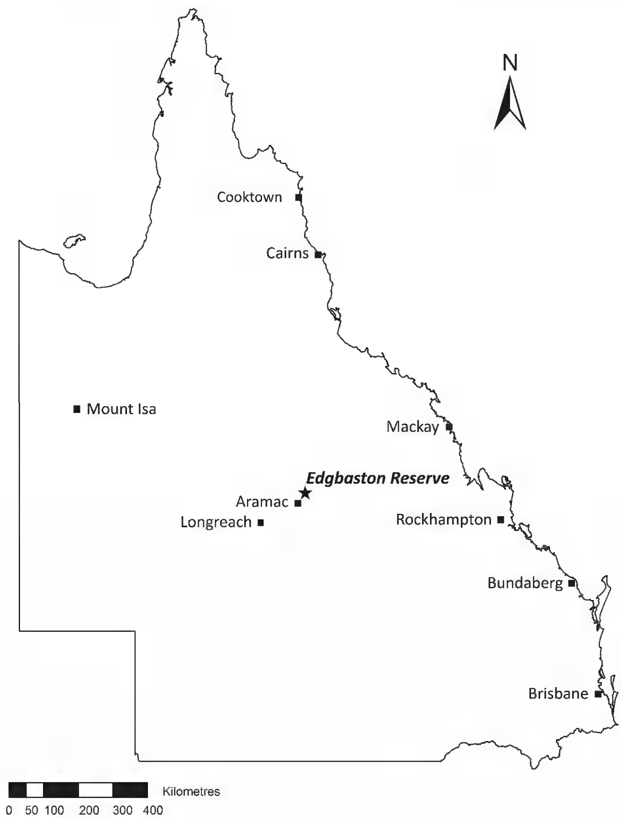
Materials and Methods

Study Location

Toads were collected from one GAB spring located within Edgbaston Reserve (Figure 1) approximately 32 km north-east of Aramac, in central Queensland, Australia (22.735218°S, 145.421172°E). The spring is located on the eastern side of Edgbaston Reserve at the base of the Desert Uplands escarpment, on the north-eastern side of the GAB (Kerezsy, 2011). There are up to 180 springs in the complex (Fensham & Fairfax, 2009) with varying surface extent. These contain the highest number of endemic macroinvertebrates of all the spring complexes in Australia (Ponder et al., 2010) and are home to two endemic fish species – the endangered red-finned blue-eye (*S. vermeilipinnis*) and the vulnerable Edgbaston goby (*C. squamigenus*).

Cane toads and macroinvertebrates were collected from spring NW30, which is situated in close proximity to other springs in the northern section of the spring complex within Edgbaston Reserve. NW30 is one of the larger springs in the complex, with a surface extent of 2723 m^2 at the time of sampling (mean extent within complex = 1155 m^2) (Blessing et al., 2012). Harsh weather conditions characterise the semi-arid climate in this area. Mean annual rainfall is 692 mm, while mean annual evaporation is over 1997 mm (EHP, 2009). Mean minimum and maximum temperatures in the area (Barcaldine) for the month of sampling (July) are 7.9°C and 22.6°C, respectively (Bureau of Meteorology, 2012). Spring NW30 is fed by warm groundwater and has a daytime water temperature range of 20–33°C throughout the year (Fairfax et al., 2007).

Figure 1. Cane toads and macroinvertebrates were sampled from within a Great Artesian Basin spring wetland located on Edgbaston Reserve, Queensland.



Sample Collection

Cane Toads

Cane toad specimens were collected during a two-person, 15-minute spotlighting survey in and around the entire extent of spring NW30 (Figure 2), during the late evening in early July, 2011. All specimens were euthanised and frozen prior to transportation to the laboratory.

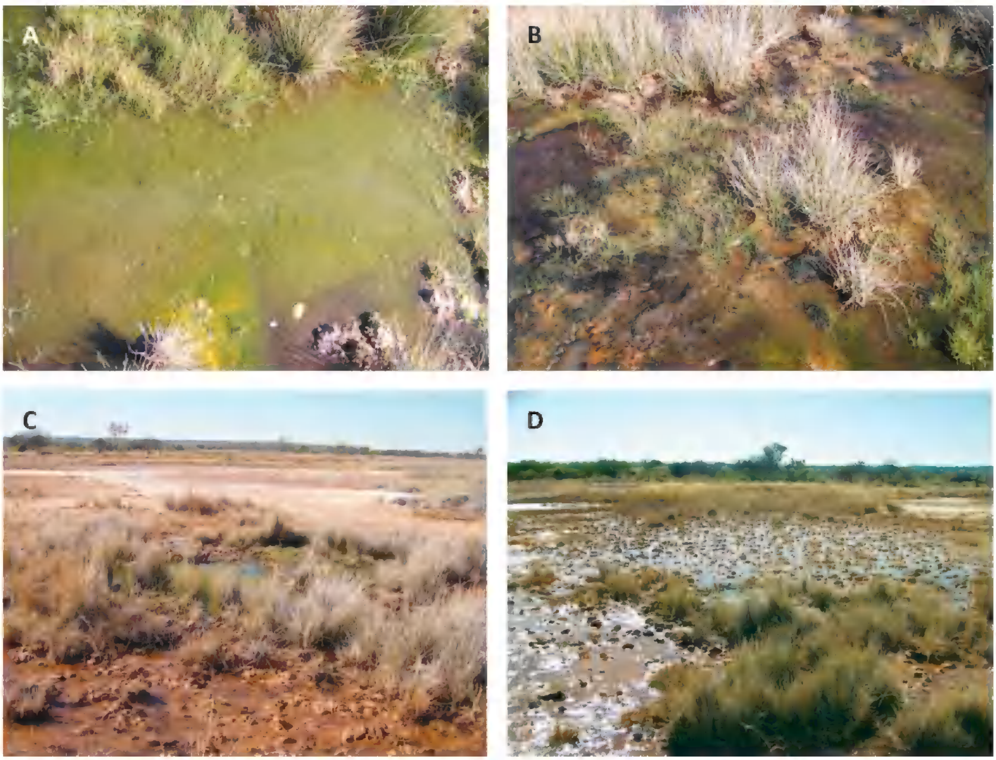
Aquatic Macroinvertebrates

Aquatic macroinvertebrates were collected from spring NW30 using a 250 µm mesh dip net. Five metres of spring habitat were sampled using a combination of short lateral sweeps (approximately 30 cm each) and vertical lifts. Macroinvertebrates were live-picked in the field and preserved in 100% ethanol for transportation. Specimens were typically identified to the taxonomic level of family, with the exception of Chironomidae (identified to subfamily), Acarina, Hirudinea, and Oligochaeta (identified to subclass), and Ostracoda (identified to class).

Laboratory Analysis of Cane Toads

Cane toads were defrosted prior to laboratory analysis, blotted dry with paper, weighed to the nearest 0.1 g, and snout-urostyle length (SUL) (mm) recorded prior to dissection. The length of the alimentary canal (mouth to anus) was removed, measured and placed onto a Petri dish lined with 1 mm graph paper. Visual assessments of both the stomach and intestinal tract were made to determine the fullness of each using the following categories: 1) Empty; 2) Little (<25%); 3) Some (25–75%); and 4) Full (>75%).

Figure 2. Photographs of a Great Artesian Basin spring wetland within Edgbaston Reserve showing (A, B) a warm spring vent; (C) spring vent encompassing the area sampled for cane toads and aquatic macroinvertebrates; (D) cooler spring outflow area – no cane toads were captured in this area.



An indirect volumetric method was used to assess the relative contribution of food items in the alimentary canal as per Hyslop (1980). Alimentary canal contents were placed onto a Petri dish sitting on top of 1 mm graph paper and compressed to a constant depth of approximately 1 mm thickness. Each food item was scored according to the number of graph paper squares covered, and expressed as a percentage of the total number of squares covered. The volumes of large items that could not be compressed were estimated.

Food items were categorised into: unidentified material, detritus and sand, aquatic invertebrates, and terrestrial invertebrates. Where possible, individual specimens were further identified to class, order or family level, and the number of each noted. Coleoptera were identified to family where possible; however, in the case of detached elytra, these were classified as 'aquatic' if they were visually identical to the elytra of beetles in the corresponding aquatic macroinvertebrate sample or to other identified aquatic specimens within the toad alimentary canal contents. Two detached elytra were counted as representing a whole specimen.

Results

Cane Toads

Thirteen cane toads (12 male and 1 female) were collected from spring NW30 during the survey, all of which were found within 3 metres of the spring vent despite the total surveyed area being larger. The mean defrosted specimen weight was 45 g (range 24.7–134.3 g); mean SUL was 76 mm (range 64–111 mm); and the mean alimentary canal length 282 mm (range 198–414 mm). Three toads had empty stomachs, while the remaining 10 contained

'little' stomach matter (i.e. <25% full). Intestinal tract fullness consisted of 4 toads with 'little' content and 9 with 'some' content (i.e. 25–75% full).

Sixty-five percent of the volume of material identified from cane toad alimentary canal contents fell into the category of 'detritus and sand' (Figure 3). Less than 2% of the material was categorised as 'undetermined digested material' that could not be identified, and this was recorded in only three of the toads. The remaining 34% of the alimentary canal contents was identified as invertebrates, represented by 15 aquatic and four terrestrial taxa. Of this volume of invertebrates, aquatic taxa made up 29.5%, whereas terrestrial invertebrates made up only 4%. Aquatic Coleoptera represented 15.8% of the volume, aquatic Gastropoda 11.4%, and the remaining 2.3% of aquatic invertebrates consumed was comprised of Acarina, Amphipoda, Diptera, Epiproctophora, Hemiptera, Hirudinea, and Oligochaeta (Table 1). On average, toad alimentary canal contents contained approximately 40 individual aquatic organisms (dominated by Coleoptera and Gastropoda) and 2 individual terrestrial organisms (dominated by the family Formicidae, i.e. ants) (Table 1).

Aquatic Macroinvertebrates

Fourteen taxa were represented in the aquatic macroinvertebrate sample collected from spring NW30 (Table 1). Specimens from the Families Dugesiidae, Leptoceridae, Culicidae and from the class Ostracoda were present in the macroinvertebrate sample but not found within the alimentary canal contents. Conversely, terrestrial invertebrates and several aquatic macroinvertebrates were found exclusively in the cane toad alimentary canal contents.

Discussion

Previous studies have identified terrestrial invertebrates as the dominant prey items of toads, though as opportunistic feeders they have the ability to impact significantly on taxa that would normally comprise only a small part of the diet (Shine, 2010). Alimentary canal contents from this study confirmed this, as, with the exception of detritus and sand, invertebrates made the largest contribution to the diets of *R. marina* collected from a GAB spring within Edgbaston Reserve. This was in terms of both contributions to alimentary canal volume and the number of individual prey items consumed.

Figure 3. Mean percentage of food items found in cane toad alimentary canal contents (n = 13). Standard error bars (±1 standard error) are shown.

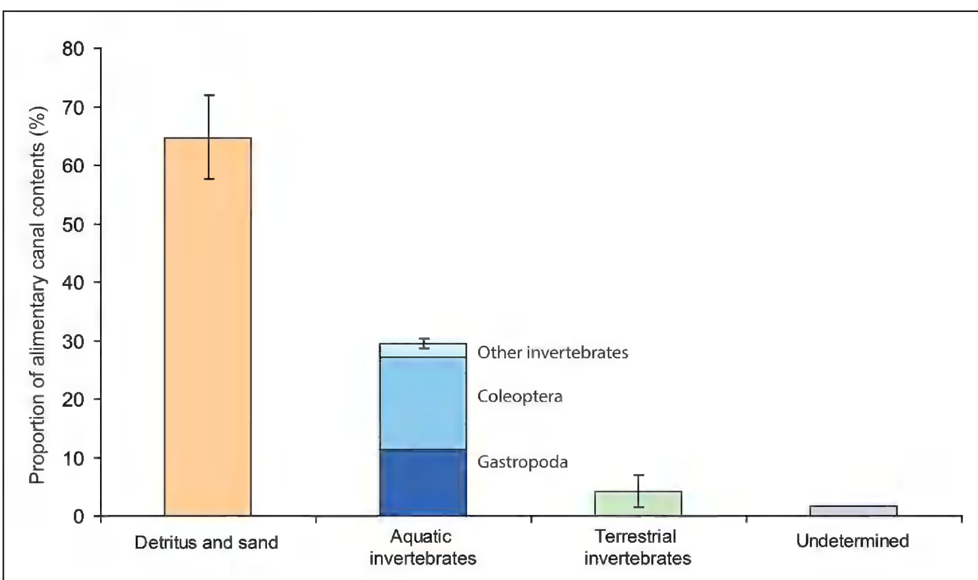


Table 1. Aquatic and terrestrial invertebrate taxa recorded from cane toad alimentary canal contents and the aquatic invertebrate sample collected from the corresponding GAB spring. Mean abundances of invertebrate taxa consumed per cane toad are shown, with ranges (minimum and maximum) in brackets.

Taxonomic group	Taxon	Present in aquatic invertebrate sample	Present in cane toad alimentary canal	Mean abundance per cane toad
Aquatic				
Acarina	Acarina	✓	✓	0.23 (0–2)
Amphipoda	Hyalidae	✓	✓	0.38 (0–2)
Annelida	Hirudinea	✗	✓	0.46 (0–6)
	Oligochaeta	✗	✓	0.08 (0–1)
Coleoptera	Dytiscidae	✓	✓	0.62 (0–5)
	Hydraenidae	✓	✗	0
	Hydrochidae	✗	✓	0.08 (0–1)
	Hydrophilidae	✓	✓	0.77 (0–4)
	Undetermined aquatic Coleoptera	✗	✓	9.54 (0–40)
Diptera	Chironomidae	✗	✓	0.08 (0–1)
	Culicidae	✓	✗	0
	Stratiomyiidae	✗	✓	0.15 (0–1)
Epiproctophora	Libellulidae	✓	✓	0.08 (0–1)
Gastropoda	Bithyniidae	✓	✓	0.62 (0–3)
	Hydrobiidae	✓	✓	25.23 (0–102)
	Planorbidae	✓	✓	1 (0–7)
Hemiptera	Corixidae	✗	✓	0.31 (0–4)
	Pleidae	✓	✓	0.08 (0–1)
Ostracoda	Ostracoda	✓	✗	0
Platyhelminthes	Dugesiidae	✓	✗	0
Trichoptera	Leptoceridae	✓	✗	0
AQUATIC SUBTOTAL				**39.71**
Terrestrial				
Araneae	Araneae	✗	✓	0.08 (0–1)
Hemiptera	Aphididae	✗	✓	0.08 (0–1)
	Other terrestrial Hemiptera	✗	✓	0.23 (0–2)
Hymenoptera	Formicidae	✗	✓	1.38 (0–10)
TERRESTRIAL SUBTOTAL				**1.77**
TOTAL				**41.48**

Cane toads were found to consume a large proportion of the available aquatic taxa, with eight of the 11 orders of aquatic invertebrates found in the corresponding macroinvertebrate sample also found in alimentary canal contents. Previous studies have shown that toads will preferentially consume small-bodied terrestrial invertebrates (Strussmann et al., 1984); however, they have also been shown to have opportunistic generalist feeding habits (Zug & Zug, 1979; Strussmann et al., 1984; Reed et al., 2007; Heise-Pavolv & Longway, 2011) which these results support. The categorisation of over half the alimentary canal contents as 'detritus and sand' (mainly sand) demonstrates the 'sloppy' feeding style of toads (Zug & Zug, 1979), which results in their often ingesting large amounts of superfluous material such as sand and detritus when capturing their prey (Hinckley, 1963; Zug & Zug, 1979).

Aquatic beetles (Coleoptera) and snails (Gastropoda) accounted for the majority, by volume and number, of the aquatic taxa consumed. Of the toads examined, 85% had aquatic beetles in their alimentary canal contents. Although gastropods were not identified to species level for confirmation of endemicity (due in part to damage during digestion), it is likely endemic species were consumed since all six snails within the family Hydrobiidae found at Edgbaston Springs are endemic, as well as one species of Bithyniidae and several species of Planorbidae (Ponder et al., 2010).

The distribution of material in the alimentary canal showed digestion of prey had already progressed beyond the stomach to the intestine, meaning soft-bodied taxa such as flatworms (the only planarian found at Edgbaston is the endemic *Dugesia artesiana* (Sluys et al., 2007)) could potentially have been consumed but already digested beyond identification (Heise-Pavlov & Longway, 2011; Zug & Zug, 1979). To minimise this, future studies could consider instant freezing using liquid nitrogen or the in-situ removal of the alimentary canal prior to transportation to the laboratory for processing.

If the abundance of aquatic macroinvertebrates consumed by cane toads continues at this rate, there is potential for cane toads to alter the spring's macroinvertebrate community. The significance of this finding is compounded given that the collection of toads for this study was undertaken during mid-winter when toad activity is suppressed by cold nightly air temperatures (Freeland, 1984) (below 0°C at the time of collection). It is of interest to note that although the sampling area encompassed the entire spring extent, cane toads were only found and collected in close proximity to the spring vent. The temperature of the discharging groundwater was warm (24°C) and remains above 20°C throughout winter (Fairfax et al., 2007). With increasing distance from the spring vent, water temperatures dropped significantly and no toads were detected more than 3 metres from the warm vents. During warmer ambient conditions or periods of higher rainfall, toads may change their diets (possibly to more terrestrial sources, lessening the pressure on the springs) as their ability to feed away from the warm spring water increases. Further diet analyses of additional toads collected from in and around the springs during warmer months and in periods of high rainfall, along with concurrent terrestrial and aquatic invertebrate sampling, are required. This will reveal if cane toads continue to preferentially feed on aquatic macroinvertebrates throughout the warmer/wetter months, exerting ongoing pressure on endemic species and communities.

Modelling using biophysical and climatic data shows that much of Queensland and northern Australia is currently suitable for cane toads, and will continue to be suitable under future climate scenarios (Kearney et al., 2008). Currently found within eastern GAB springs in Queensland (Fensham et al., 2010), cane toads have the potential to continue expanding their range to other GAB spring communities and wetlands in regions characterised by a scarcity of surface water.

This initial investigation supports the notion that cane toads can directly impact GAB spring communities via predation of aquatic invertebrates. It is possible that the local consequences of this could be significant, given the small spring size and the endemicity of the aquatic invertebrate fauna. The trophic cascade caused by the feeding habits of cane toads could also pose a threat to spring communities, as experimental studies have attributed changes to terrestrial/floodplain invertebrate community assemblages to cane toad predation (Greenlees et al., 2006; Shine, 2010). Large numbers of cane toads in areas of the Northern Territory have also been identified as the apparent

cause of reductions in both the abundance and species diversity of insectivorous reptiles due to the depletion of their food supply (Catling et al., 1999).

These results suggest that in addition to current practices to manage threats (see Kerezsy, 2011), management of the springs within Edgbaston Reserve could consider incorporating measures to reduce toad abundance or prevent them from accessing springs. That cane toads seem to congregate around the spring vents could also aid in the collection/extermination of toads during the colder months, as the vents act as a lure. Recent advances in cane toad control using fences (Florance et al., 2011) and pheromones (an alarm pheromone and an attractant pheromone can be used respectively to selectively kill or attract the tadpoles) (Crossland et al., 2012; Crossland & Shine, 2012) may provide solutions.

Further research and monitoring is required to better establish the threat the cane toad poses to GAB spring communities. This includes establishing an accurate distribution map of cane toads at GAB springs, as well as establishing if the cane toads are breeding within the springs. In addition to cane toads, the viability of endemic spring species is also at risk due to multiple additional threats, including mosquitofish (*Gambusia holbrooki*) and feral pigs (Fensham et al., 2010). Further research to inform the ongoing management of each individual threat is required to ensure conservation of these unique ecosystems.

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Author Profiles

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Development, Management and Rehabilitation of Water Bores in the Great Artesian Basin, 1878–2020

Lynn Brake[1]

Abstract

First Nations people have depended on water from the Great Artesian Basin (GAB) springs for tens of thousands of years. The scientific exploration and development of the GAB by European settlers commenced following the construction of the first artesian bore in 1878. The use of its waters was pivotal to pastoral use of vast areas of arid and semi-arid landscapes in Queensland, New South Wales and South Australia. By 1915, more than 1500 bores had been drilled into the GAB; many were artesian free-flowing bores, with distribution losses that exceeded 90% of the water reaching the ground surface. Over time, significant pressure declines were observed with reduction in bore flow rates, and in some cases artesian bores ceased to flow. Governments and water users debated for the next half-century about how to control flowing artesian bores and to reduce the waste of precious water from the GAB. During the second half of the 20th century, significant progress was made to arrest pressure decline across the GAB. However, substantial changes occurred only as a result of basin-wide initiatives supported by state and federal governments and water users at the beginning of the 21st century. These initiatives led to the development of a GAB Strategic Management Plan and the Great Artesian Basin Sustainability Initiative (GABSI) joint funding initiative. Although investments by governments and water users were key drivers of more efficient water delivery infrastructure, sustained cooperative actions and landholder behavioural change proved invaluable in instigating and realising the change. Yet the transition to closed water delivery systems is not complete. There are now more than 50,000 bores in the GAB, of which 6600 are artesian bores, and at least 430 of these bores remain uncontrolled. Bores will continue to fail, and delivery infrastructure will require continuous maintenance. Valuable lessons from the past 120 years of GAB management can guide future management and investment decisions concerning the extraction of water from this valuable resource.

Keywords: springs, free-flowing artesian bores, distribution losses, Great Artesian Basin Sustainability Initiative (GABSI), closed delivery systems, future GAB management

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Introduction

Springs are natural surface expressions of the GAB, formed within an otherwise arid landscape over geological timescales. As a result, living communities, including humans, that depend on permanent water for survival have concentrated in and around springs, and have adapted and evolved to take advantage of the water and the physical conditions and processes that sustain them (GABCC, 2016). For tens of thousands of years, human use of water from the GAB was confined to springs flowing from a very small proportion of the basin's extent. Springs were the only reliable source of water for people across the vast arid interior of the basin. Consequently, these islands of wet in the otherwise dry landscape often became important cultural sites on the trade routes and story lines leading across inland Australia. Springs were also prime sites for hunting and more permanent camps.

In the 19th century, springs enabled early European explorers, such as John McDouall Stuart's crossing of Australia from south to north

(Figure 1), developers and traders to traverse arid central Australia (GABCC, 2011a). Not surprisingly, the route of the telegraph and railway lines through northern South Australia followed the 'spring route'. Indeed, given the absence of other sources of water, it was the only viable route (Blake & Cook, 2006). This relatively limited use of GAB water did not materially affect the water balance in the basin; however, local flora and fauna sensitive to the usage of groundwater may have been affected (National Water Commission, 2013), and no doubt Aboriginal sites and uses were affected.

This paper reviews the exploration, development, management and rehabilitation of water bores in the Great Artesian Basin from 1878 to the present. The major themes of the paper are the effects of water extraction and use on artesian pressures and bore flow rates, and the history of efforts to control flowing artesian bores and reduce wastage of the GAB water resource. The paper also points to the importance of continuing to efficiently construct and maintain the basin's water infrastructure.

Early Exploration and Development

In 1878, the first recorded artesian bore in the GAB – the 'Wee Wattah' bore – was drilled on Kallara Station, near Tilpa in western New South Wales. During a drought in 1878, a bore was drilled in the bottom of an existing well using a cable-tool rig. At 53 metres depth artesian water (water flowing to the surface due to aquifer pressure) was encountered. This bore, when combined with other such discoveries and hydrological studies performed along the Darling River system in the 1880s, suggested that further extensive reserves lay elsewhere.

During the next decade, bores were drilled in South Australia and Queensland. In 1885, investigations headed by Dr R. L. Jack (Government Geologist) and Mr J. B. Henderson (Hydraulic Engineer) led to the first artesian water bore drilling program at Blackall, Queensland, using a Pennsylvanian Walking Beam Oil Rig (Figure 2), with eventual success in 1888.

A great deal of public and government interest flowed from these initial successes, and widespread artesian exploration followed. In Queensland, pastoralists had invested more than £2 million in drilling bores by 1910 (Blake & Cook, 2006), and 364 bores had been sunk in New South Wales. During the 'artesian age', bores were constructed not only for the pastoral industry, for both sheep and cattle grazing (Figure 3), but also for new railways, mines, baths and spas, water-intensive industries and domestic and town supplies (GABCC, 2014a).

Changing Artesian Pressures and Flows

The construction of bores altered the steady-state hydrological conditions that had prevailed in aquifers over geological timescales. The extraction of water caused a depression in the potentiometric surface (pressure surface) near the bore. The depression in pressure soon meant that flows from individual bores decreased and the pressure at individual bores fell. This is a natural and predictable result of water extraction. As more water is taken from the system, water needs to flow through the system to discharge points, and the gradient increases to allow this extra flow to occur. Hence, pressure heads fall and flows from bores reduce, as does the flow to nearby artesian springs (Queensland Government, 1955).

More than 1500 artesian bores had been drilled into the basin by 1915, some to a depth of more than 1200 metres with a pressure head exceeding 200 psi and a surface temperature over 90°C. At that time, a reduction in water pressure and volume was emerging across the basin, and governments recognised that control over groundwater extraction in the basin was inadequate (Figure 4).

Early Government Response

Governments recognised issues surrounding the control of flowing bores around the turn of the 20th century, and these remained a major management issue for more than 100 years. Legislation for the management of the GAB was passed in Queensland in 1910: the *Rights in Water and Water Conservation Utilisation Act 1910*. This followed the earlier failure of the Water Supply (Wells and Tanks) Bill of 1891 to control artesian water, and the *Artesian Wells Act 1897* in New South Wales. Both Acts claimed artesian water for the state, overturning English common law (Blake & Cook, 2006). South Australian legislation passed in the 1920s contained regulations pertaining to the drilling and use of GAB bores for watering stock.

Figure 1. A map of John McDouall Stuart's route of exploration following GAB springs across central Australia, 1858–1861 (Source: The Journals of John McDouall Stuart, 1865).

Figure 2. A schematic of a Walking Beam Drilling Rig (Source: Uren, Petroleum Production Engineering, 1946; accessed at https://www.elsmerecanyon.com/oil/cabletoolrig/cabletoolrig.htm).

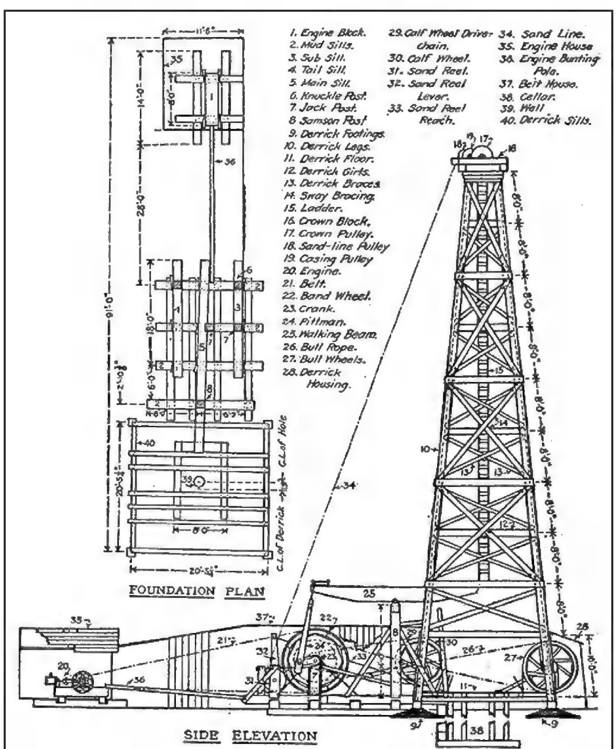


Figure 3. Free-flowing bore on stock route in western Queensland. Bores became an essential part of the developing stock route network in Queensland (Source: John Oxley Library #109157).

Systematic investigation of the impacts of artesian extraction increased markedly as a result of five interstate conferences on artesian water held from 1912 to 1928 (ICAW, 1913, 1914, 1922, 1925 and 1929). The objective of these conferences was to study the extent of the GAB, the origin and movement of the groundwater and the subsequent reduction in pressure causing diminution or cessation of flows. Well-casing corrosion problems and a more responsible utilisation of groundwater were also on the agenda.

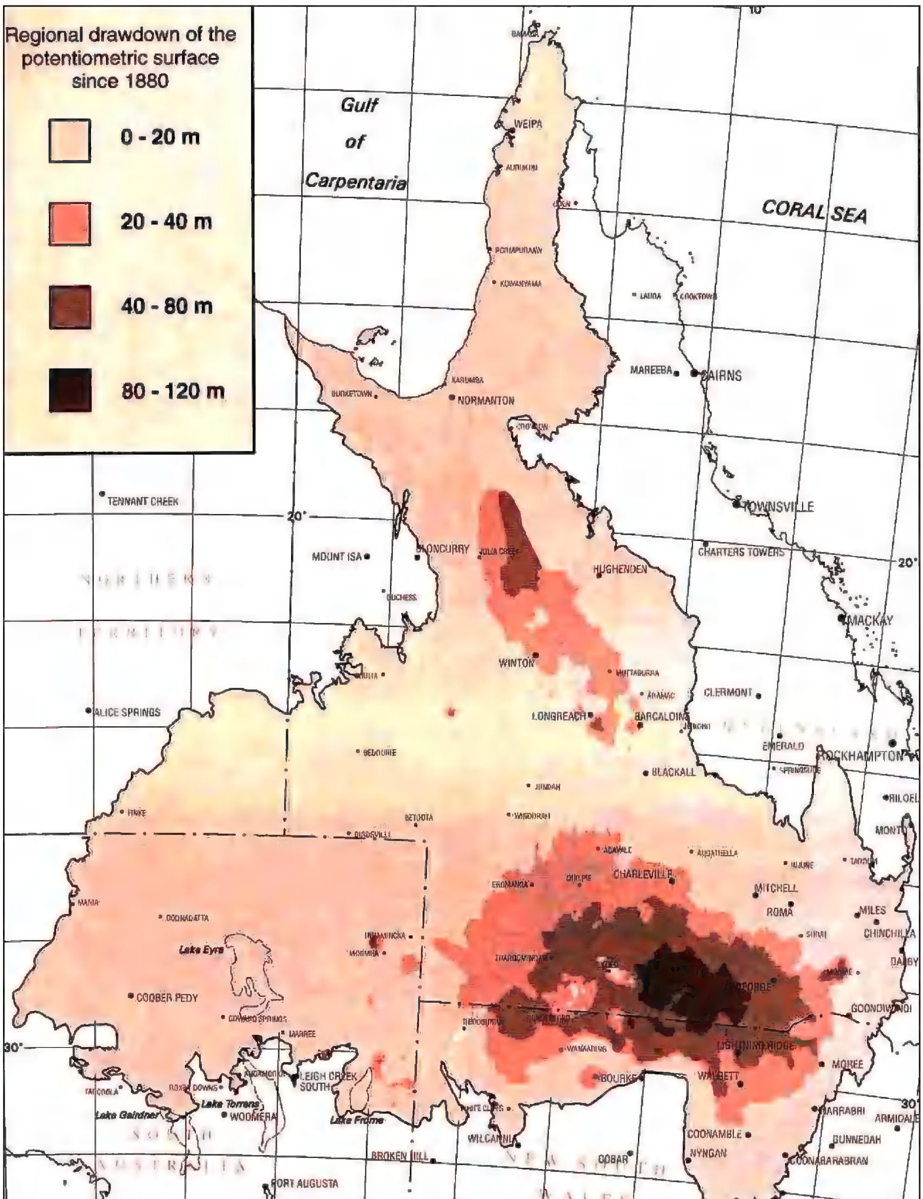
In October of 1914, the Chairman of the Interstate Conference on Artesian Water, Mr E. F. Pittman, stated in his report to the Queensland Premier:

> … insomuch as the artesian supply is a national asset, every member of the community has an interest in its (the GAB's) conservation. We venture to urge, therefore, that no person should be allowed to put down a bore unless he be prepared to observe the precautions necessary to minimise waste or leakage (ICAW, 1913).

During the 1920s and 1930s, several surveys of the section of the GAB within New South Wales were completed. They addressed the full spectrum of hydrogeological properties and included newer concepts of elastic storage. Recommendations were made for water conservation by partially closing wells and improving distribution methods for the artesian water. The next GAB interstate conference was not, however, until 1939. That meeting identified water wastage from free-flowing bores as the major management problem, and commissioned a report to investigate the nature and structure of the GAB (Tandy, 1939, 1940). The report was completed in 1945; however, it was not until 1954 that the Artesian Waters Investigations Committee provided a published report which was addressed separately by each state. The Queensland report concluded that "artesian diminution in Queensland constitutes a disability, its incidence, particularly from the economic viewpoint, is far less serious than was feared in many quarters when the investigation was commenced". The committee, however, was of the view that changes in policy and practice were necessary. For example, in 1955 regulation was introduced in Queensland which required new bores to properly control discharge with headworks and to minimise

inter-aquifer leakage and contamination from surface sources with cement grouting of bore casing (Queensland Government, 1955). The distribution of water from new bores had to be in piped systems; however, the ongoing use of existing bore drains was permitted.

Figure 4. A depiction of regional declines in artesian pressure across the Great Artesian Basin since 1880 (Source: Queensland Government, 1955).



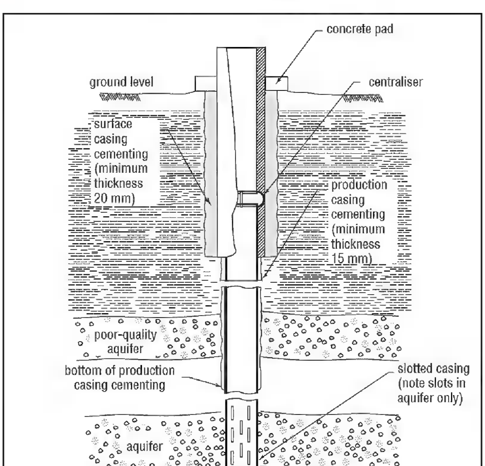
Water Bore Construction

In the early days of GAB development, bores were unable to be shut in due to completion methods. The flow from bores could not be controlled: bores often developed large pools around the bore head, and these discharged into watercourses. Most bores discharged at rates well in excess of the bore owner's requirements.

Construction Standards

Discussions on the appropriate methods of drilling and construction of artesian and sub-artesian bores took place at the 1912 Artesian Conference held in Sydney. This was an attempt to establish improved construction standards throughout the GAB. During this early period there was debate around 'best practice' bore construction, and techniques for bore construction improved over subsequent decades. For example, the development of pressure cementing (Figure 5), in which cement is pumped into the bore hole between the formations and the outer casing, made reliable construction and control of artesian bores possible. Pressure cementing was well developed and extensively used by 1940, reducing the risk of water leaking up the outside of the casing, and providing protection from corrosion of the casing as well as reduced aquifer flow (GABCC, 2014a).

Figure 5. A schematic of a multiple-aquifer artesian bore using pressure cement (Source: http://directdrill.com.au/bore-design-common-types/).



Drilling Techniques

The very earliest type of drilling employed in the GAB used 'cable-tool' rigs. These rigs used a type of percussion drilling which involves the repetitious lifting and dropping of a string of solid steel drilling tools suspended from a wire rope. The early drilling rigs were steam powered (Figure 2), requiring large quantities of wood and water to operate. As a result, bores were often sited near waterholes and alongside creeks to limit cartage of the large volumes of water and timber required to keep the rigs operating. The proximity of the resulting bores to the creeks meant that the natural waterlines were the obvious distribution networks once the work was complete.

Mud-rotary drilling became available around 1910 but was not used extensively for water bores in the GAB until the early 1960s. The rotary mud process involves pumping down a mixture of drill fluid through the rod string to cool the drill bit, while the ability for the drill crew to mix additives into the drill fluid increases well stability. This technique enabled the boring of deep artesian wells to be carried out much more easily. Rotary-mud drilling is now the most widely used method of drilling in the GAB (Figure 6). Techniques used in rotary drilling have also allowed new, corrosion-resistant casing to be used in place of steel casing, allowing longer lives of bores in areas of corrosion (GABCC, 2014a).

Methods of Water Distribution

Distribution by Drains

As artesian bores became more widespread and landholders developed an improved understanding of the artesian conditions of the GAB, the benefits of distributing water by man-made artificial channels (known as bore drains) was recognised as a way to use the resources to best advantage (Figures 3 and 7). Drains also provided a way to 'cool' the high-temperature water (up to 100°C) flowing from some artesian bores, with water dropping to a drinkable temperature over the length of bore drain systems. The use of bore drains led to less water being discharged directly into watercourses, and the bores being sited in more elevated areas to facilitate the required gravity feed via the drains.

Although losses from evaporation and seepage in bore drains account for up to 90 per cent of the

total bore discharge, a system of open drains was the only economically viable water distribution option for many decades, and extensive networks were developed (Figure 7). A Queensland study in 1952 found that stock watering, evaporation and seepage requirements for 21,000 kilometres of drains surveyed were on average 44 cubic metres (44,000 litres) of water per day per kilometre of drain length (m^3/d/km) (Queensland Government, 1955). The distribution of water via drains was a great feat of 'bush engineering', with some individual drains taking water many hundreds of kilometres. In some cases, aqueducts were used to traverse creeks, with divisors to distribute the correct volumes where drains divided to supply different properties.

Drains require routine maintenance to continue to deliver water. The principal maintenance procedure ('delving') is a process whereby the drain is reshaped by a plough-like implement that is pulled through the drain. This dislodges sediment and other loose material from the base of the drain and plasters it back along the sides (GABCC, 2014a). This was also required after flood events when drains were often washed away, or due to stock damage, with drains often breaking out, creating pools and disrupting natural water flow.

Flowing bores and bore drains were an established part of local cultures in pastoral communities for many years. The first accurate account in Queensland, from 1949, documented 26,900 kilometres of bore drains (Queensland Government, 1955). The average bore drain length for trust bores (bores serving two or more properties) in Queensland at the time was 80 kilometres. The longest drains exceeded 150 kilometres. In New South Wales the total length of bore drains in Bore Trust areas increased from 4200 kilometres in 1915, to 5200 kilometres in 1950, and 5800 in 1970.

Figure 6. A rotary drill rig being used on a 1200-metre bore in the Great Artesian Basin (Source: Daly Brothers Drilling; available at http://www.dalybros.com.au/).

Figure 7. Open bore drains running from a controlled bore on a property near Julia Creek in Queensland (Source: GHD, 2019).

Effect on the Environment

The distribution of water in the landscape by artesian bores results in permanent water being available to grazing animals over millions of hectares that were once very distant from permanent surface water. Natural water scarcity limits and controls the distribution of many species of plants and animals in such areas. Some mammals such as bilbies and dunnarts, as well as many insect-eating birds and reptiles, survive without drinking. Some animals such as kangaroos and parrots have restricted distributions during drought, retracting to the vicinity of waterholes and springs. Stock and many other animals were previously only able to range into arid areas following rain. Additional watering points change the total grazing pressure on plant communities. Areas watered by bore drains and piped, dispersed watering points become accessible to stock as well as native animals and feral animals (GABCC, 2011a). Feral grazers such as pigs, goats and rabbits, as well as predators such as cats and foxes, can benefit from access to water. Predators and feral animals compete with many smaller native animals for habitat and food, and many natives are preyed on directly by feral predators (Noble et al., 1998). Work in Queensland showed that few parts of the state now had water remote status. Only four GABSI program properties had significant areas greater than 6 km from bore drains, and on these properties the policy was that government would negotiate with landholders to seek alternative watering points to maintain this water remoteness (Department of Environment and Resource Management, unpublished report, 2009).

Another issue was the environmental value of the drains themselves. Research in the late 1990s and 2000s around bore drains and artificial wetlands created by them, some of which were now over 100 years old, showed that most provided no positive environmental benefit. However, in South Australia, five bores east of Lake Eyre South were considered to offer potential habitat to a range of

fauna species, particularly birds (Kinhill, 1998), and some wetlands had both social and ecological importance to pastoralists in South Australia (Centre for Environmental and Recreation Management, 2002). New South Wales legislation saw no value in conserving bore-fed wetlands; however, South Australia permitted a small subset of bore-fed wetlands or drains to remain. More recently, a Queensland study of bore drains near Aramac found endemic spring flora (*Myriophyllum artesium* and *Eriocaulon carsonii*) in one drain-fed wetland, and the endangered Edgbaston goby (*Chlamydogobius squamigenus*) has been recorded in a bore drain 20 km from its native natural spring habitat, suggesting that some remaining Queensland drains may have conservation significance (Kerezsy, 2020).

The flow of artesian water across the landscape, which is often alkaline and highly sodic, results in a range of deleterious changes, including: scalding due to increased salinity; physical deterioration of the soil; hardening; and increased soil erosion (GABCC, 1998; Biggs & Binns, 2015). The seepage and wall breaches of bore drains caused the same type of problems that large-scale irrigation causes on a massive scale, and bore drains have left a large legacy of salts in soils over thousands of kilometres. Bore drains also become important transmission vectors for weeds, especially new weeds of national significance: mesquite, prickly acacia and parkinsonia. Rehabilitation of bore drains without simultaneous weed control can lead to ongoing legacy issues (DAF, 2016).

Distribution by Piping

The idea of distributing artesian water by means of pipes (Figure 8), instead of drains, was mooted as early as 1912 at the Interstate Conference on Artesian Water. The feasibility of piping was raised but was considered so costly as to be 'impossible', as the best available piping material was galvanised steel. The cost-effectiveness of piped systems changed as infrastructure materials improved (e.g. polypipe and mass-produced concrete tanks and troughs) and new technologies and ripping with bulldozers and pipe-laying machinery were introduced, and landholders developed a better understanding of the benefits that accrued from well-designed, efficient systems.

Figure 8. Replacement of bore drains with polypipe to create closed water systems (Source: DNRME).

According to pastoralists who moved to closed water delivery systems, replacing bore drains with piped systems can improve productivity and property management practices (Centre for International Economics, 2008), including:

- the elimination of all costs associated with bore drain maintenance and repairs, such as delving, repairing breakouts and bore drain inspections;
- reduced mustering times and more simplified mustering processes;
- better utilisation of all natural resources on the property through better water distribution;
- more flexible and efficient property management – by controlling watering points, grazing pressure can be better managed, thereby improving both native vegetation health and livestock performance;
- having clean water for stock to drink;
- having pressure and clean water at the homestead;
- the ability to better control vertebrate pests, thereby reducing control costs;
- reduced costs of controlling weeds which can be spread along bore drains;
- avoiding increased pumping costs where artesian wells might otherwise turn subartesian;
- increased security of water supplies, thereby reducing management anxiety; and
- improved scope to better manage in times of drought.

Well designed and constructed piped systems require relatively little maintenance. A cost analysis of piping schemes in South West Queensland covering the period 1994–1999 found that the operating costs of bore drains were much greater than those of piped water systems (Pegler et al., 2001).

Bore Rehabilitation Activity

Pre-1999 Bore Rehabilitation

Although some water efficiency gains were made over the first half of the 20th century, water pressures in many regions continued to diminish, springs and bores stopped flowing, and valuable water resources continued to be wasted. Both a policy response that effected change in management practices and coordinated assisted funding to rehabilitate the water infrastructure were required. Without political recognition of the public benefits from preserving artesian pressure and reducing wastage, too little was being done to control bores and rehabilitate water delivery infrastructure.

Repairs to bores were carried out by some landholders, when needed, but most were content to leave their bores to flow into bore drains at capacity. Rehabilitating bores and piping water supplies were expensive, and few schemes to repair bores and replace existing bore drains were undertaken voluntarily. State governments slowly recognised the need to control bores and replace bore drains, and commenced new work in the 1970s with various levels of federal government assistance. The Great Artesian Basin Bore Rehabilitation Program (GABBRP) stemmed from a government report recommending that closed systems be funded (Woolley et al., 1987). Table 1 summarises the results of capping and piping programs in the GAB before the commencement of the national Great Artesian Basin Sustainability Initiative in 1999.

Table 1. The results of Great Artesian Basin renewal programs across Australia between 1977 and 1999 (GABCC, 2014a).

Pre-GABSI	Bores controlled	Bore drains removed (km)	Piping installed (km)	Water saved per year (ML)
Queensland	327	1,843	2,698	72,476
New South Wales	86	1,391	2,812	9,051
South Australia	230	not known	not known	39,542
Northern Territory	3	not known	not known	6,000
Total	**646**	**3,234**	**5,510**	**127,069**

South Australia

In 1977, following a request from the South Australian Water Resources Council, the South Australian Government prepared a report that identified the uncontrolled wells in the South Australian portion of the GAB. As a result, a bore rehabilitation program commenced that year. Initially, the program concentrated on rehabilitating bores drilled for seismic and exploration purposes west of the Peake and Denison Ranges, but it was later extended to include all uncontrolled flowing bores. Since bores in South Australia were originally government drilled and owned, bore rehabilitation was 100 per cent government funded with no landholder input required. Commencing in 1977, 230 government-drilled wells were rehabilitated. This number does not include bores that were plugged and abandoned, or repairs conducted only on headworks. No subsidy was offered to landholders for piped distribution systems, although some were privately installed (Centre for International Economics, 2008).

New South Wales

From 1952 to 1976, the government drilling unit based in Dubbo rehabilitated 348 flowing bores. Sixty-nine bores were rehabilitated during the initial phase of this work (from 1952 to 1956). This was followed by minimal activity from 1957 to 1960 while the impact of the work was determined. Total flow from bores in New South Wales had fallen from 179,000 ML/year in 1914, to 106,000 ML/year in 1952, and continued to fall further to 95,000 ML/year by 1958. At that time the decline was reversed as additional bores were drilled and the use of bore drains persisted; flow once again increased to 106,000 ML/year. When the project ceased in 1976, the flow had been re-established at 118,000 ML/year and was continuing to rise.

The next rehabilitation program was GABBRP, which commenced in 1990 with the aim of rehabilitating and controlling artesian bores in the New South Wales section of the GAB, mirroring a similar program in Queensland. An 80 per cent subsidy was provided for bore rehabilitation, but no subsidy was available for piping. Further developments saw the introduction of the Cap and Pipe the Bores Program, which continued the subsidy for the rehabilitation of bores and provided a 20 per cent subsidy for the piping component from mid-1993. Under these programs, 86 bores and their distribution systems had work completed, resulting in water savings of 9051 ML/year and 1391 kilometres of drains removed. The programs installed 2812 kilometres of piping (GABCC, 2014a).

Queensland

Significant interventions to systematically address bore rehabilitation began in the mid-1980s in Queensland. Three separate capital works projects provided subsidies using both federal and state funds. These were:

1. The GAB Rehabilitation Project (GABBRP) 1989–1999.
2. The Bore Drain Replacement Project (South West Strategy) 1994–2001.
3. The Bore Drain Replacement Project (Drought Regional Initiative/Outside the South West Strategy) 1995–2001.

The GABBRP, which provided financial and technical assistance to bore owners to repair uncontrolled artesian bores, commenced in 1989 and required bore owners to pay 20 per cent of the cost of bore repair or replacement. The program repaired, relined or replaced 327 bores. A total of 43,122 ML/year was saved by these works. The two bore drain replacement projects, the South West Strategy and the Drought Regional Initiative, were very similar projects. The former operated in the south-western Queensland area, and the other applied to drought-affected areas of western Queensland. The only significance difference in the way they were managed was the level of subsidy provided. During the operation of these programs, the drains of 61 bores were replaced by piping schemes, thus replacing 1843 kilometres of drains with 2698 kilometres of piping and saving a total of 29,843 ML/year (GABCC, 2014a).

Northern Territory

The Northern Territory had three bores in the GAB, all of which were flowing uncontrollably. In the 1990s all were brought under control or plugged with total water savings of 6000 ML/year.

Summary

Rehabilitation projects in each of the jurisdictions from 1954 to 1999 brought some incremental improvements in water use efficiency; however,

lasting solutions to basin-wide water access and distribution problems still proved problematic. Existing programs were inadequate to address the need for water infrastructure renewal and maintenance across the GAB within a reasonable time frame, although progress had been made in each jurisdiction. This untenable situation was exacerbated by little recognition from governments and the wider community of the value of the GAB to the Australian community or the imperatives of sound groundwater management.

The GAB Strategic Management Plan and GABSI

A Transitional Period for the Pastoral Industry

Despite significant funding and investment programs in the mid-1990s, there were still 3358 flowing bores and more than 34,000 kilometres of bore drains in the basin. There was continued decline in artesian pressures in most regions of the basin, threatening the health of the GAB and spring ecosystems, impacting on existing water users and limiting opportunities for new water uses.

In 1997, a meeting was held in Brisbane between government management agencies, GAB water users and other interests to evaluate progress towards achieving a timely solution to long-standing issues surrounding uncontrolled bores and the use of bore drains. Following extended discussion, the meeting agreed that a coordinated basin-wide approach was required. The discussion resolved that successful bore rehabilitation would require:

- a policy response from governments to clarify users' rights and responsibilities;
- a change in local culture for many landholders, resulting in improved on-ground management practice; and
- an agreed basin-wide investment response to capping and piping bores from landholders and governments.

The major outcomes from the meeting were:

- the establishment of a Basin-wide Consultative Committee; and
- a process to develop a Strategic Management Plan (SMP) for the GAB.

The responsibility for GAB management remained with the states; however, the establishment of the Basin-wide Consultative Committee and its successor the Great Artesian Basin Coordinating Committee (GABCC) proved to be an important initiative in facilitating the required cooperative approach to capping and piping bores. Over the next two years, federal and state governments worked cooperatively with the GABCC, water users and other interests to complete the first GAB Strategic Management Plan (SMP). The SMP was subsequently agreed to and signed by Water Ministers from each of the jurisdictions in 2000 (GABCC, 2000).

The major focus of the SMP was rehabilitating uncontrolled bores and replacing bore drains with piping. A key driver for the implementation was the governments' agreement to the first phase of the national program called the Great Artesian Basin Sustainability Initiative (GABSI). The implementation of the SMP and GABSI was the beginning of an 18-year period of renewal in the pastoral industry. During this transition period, the actions of governments and landholders working together eliminated over 70 per cent of uncontrolled bores and bore drains.

Great Artesian Basin Sustainability Initiative (GABSI)

GABSI was a joint program between the Australian, New South Wales, Queensland, South Australian and Northern Territory governments and basin landholders. It was initiated in 1999 to be implemented over three five-year funding rounds; it would be subject to review every five years and, depending on outcomes, revised and funded again over the next five-year period. The public benefits used to justify the GABSI investment centred on water savings, pressure recovery, sustaining GAB spring flows and avoiding market failure for pastoralists in the GAB (Hassall, 2003). GABSI provided a substantial financial input, leading to an accelerated program to assist landholders in the rehabilitation of bores and water delivery infrastructure (Tables 2, 3).

A mid-term independent review of GABSI Phase 3 found that the program was highly successful and appreciated by stakeholders. Rehabilitation of high-flow bores remained a high priority in GABSI Phase 3, but for landholders yet to rehabilitate bores or bore drains on their land, the cost

and resistance to change were the main deterrents (GABCC, 2011b).

On 16 October 2014, the Australian Government announced the extension of the GABSI program for an additional three years through to 30 June 2018 after the review indicated that progress had been curtailed due to low commodity prices and drought creating problems for landholders to meet funding requirements. This extension provided governments the opportunity to work with industry and communities to develop a private sector model for water infrastructure maintenance and replacement in anticipation of the drought ending.

Table 2. Activity under the Great Artesian Basin Sustainability Initiative (1999 to 2018): bores controlled, open bore drains removed and water saved (Source: DAWE, 2020).

State	Bores controlled	Bore drains removed (km)	Water saved (ML/year)
Queensland	397	12,491	139,081
New South Wales	311	8,558	68,830
South Australia	51	342	48,961
Total	**759**	**21,391**	**256,872**

Table 3. Investment by governments in each phase of the Great Artesian Basin Sustainability Initiative (Department of Agriculture, Water and the Environment, 2020).

Jurisdiction	GABSI 1: 1999–2000 to 2003–2004 ($ million)	GABSI 2: 2004–2005 to 2008–2009 ($ million)	GABSI 3: 2009–2010 to 2013–2014 ($ million)	GABSI 4: 2015–2016 to 2017–2018 ($ million)	Total
Australian Government	28.386	38.531	44.644	13.401	124.962
QLD	14.304	22.736	23.706	3.996	64.742
NSW	12.335	15.595	18.011	2.78	48.721
SA	1.747	0.200	2.927	6.625	11.499
Total	**56.772**	**77.062***	**89.288**	**25.961**	**249.924***

*In addition to totals shown, landholders contributed $50+ million, as shown in the Implementation Plans against each year. Landholder contributions were different in each jurisdiction and from year to year due to flood events, drought, and capacity of landholders to invest.

Government Activities

In 1999 at the beginning of GABSI, each jurisdiction government started from different positions in policy, regulation and on-ground investment. All state agencies had drilling, logging, monitoring and technical/information crews working with landholders in bore rehabilitation and stock water delivery projects. This created different expectations concerning government and landholder responsibilities for the capping and piping roll-out. Participation in GABSI was voluntary, so landholders were free to decide whether changing practices was in their best interest. For example, in Queensland local cultures continued to support long-standing traditional stock watering practices centred on bore drains and pumping from ‘turkey nests’ (above-ground dams completely enclosed by earth embankments). Landholders generally resisted change.

State water management agencies were actively involved in bore assessment and rehabilitation, and each determined the requirements for GABSI in different ways. Each interpreted criteria for eligibility, priorities, entitlements, cost sharing and implementation differently and readjusted at the beginning of each GABSI funding period (Commonwealth Government, 2010). The acceptance by regulators of existing inefficient water management practices (e.g. use of drains, combined with the traditional

technical support from government drillers and technical staff) created expectations amongst some landholders that the responsibility for change rested mainly with governments (Centre for International Economics, 2008).

Governments initiated a wide range of education and information initiatives in support of GABSI designed to change existing perceptions and attitudes amongst landholders and encourage the installation of more efficient water management practices. The GABCC, state advisory and other government-sponsored groups organised and participated in field days (Figure 9), technical workshops, trials, and demonstrations in special workshops and numerous community events. Landholders participated in a 'GAB Champions' campaign which identified and supported advocates for closed water delivery infrastructure.

Information products included: case studies; GAB maps and posters; and DVDs and booklets on the GAB and efficient watering systems. GAB researchers' forums were held in basin states. The CSIRO completed a major investigation into efficient stock water management in the pastoral industry (James & Bubb, 2008). Governments produced technical brochures on the design, installation and maintenance of water infrastructure. The media published articles and screened television programs on GABSI and the value of rehabilitating bores (SKM, 2008).

Policy responses at the beginning of the transition period consisted mainly of information about the benefits of efficient water management systems, along with assistance with infrastructure design and installation. The key message to water users was that changes in regulations were coming, and closed water delivery systems would be required at some time in the future. During the transition period, all jurisdictions developed or adjusted statutory plans and incorporated regulations to clarify the rights and responsibilities of landholders to use water judiciously and eliminate waste. As the transition progressed, policies concerning the rights and responsibilities of landholders and the role of governments for water infrastructure rehabilitation and maintenance changed. Community and industry attitudes shifted towards the need for more efficient water delivery systems (GABCC, 2014a).

Figure 9. Field day for landholders about water management in the Great Artesian Basin (Source: Great Artesian Basin Coordinating Committee website).

A core purpose of the GABSI program was to protect GAB springs, and the basin states put in place programs specific to this aim. In Queensland under the Blueprint for the Bush plan, the then Department of Natural Resources and Water committed $500,000 in 2006–2007 for the next three years to help rural landholders rehabilitate nine of the most difficult free-flowing bores in the GAB. The high-risk bores were bores that had deteriorated to a state where there was no visible bore casing and a pool had formed at the surface. The condition of the bore makes it very difficult to estimate the cost of rehabilitation, and as a result the bore owners are reluctant to participate in GABSI. The Blueprint for the Bush funding addressed this by capping the landholder's contribution to accessing and plugging the bore to $20,000, with the remaining project cost under GABSI met from the Blueprint for the Bush funding.

Statutory water allocation plans of each state jurisdiction included regulations that require closed water delivery systems by the end of the transition period. Water plans that included provisions that artesian systems be made watertight commenced in New South Wales in 2008, with a sunset clause to 2016, South Australia in 2009, and Queensland in 2017 (DAWE, 2020).

Technology – Change and Challenge

In 1983, jurisdictional governments organised a Technical Working Group (TWG) with hydrogeologists, government drillers and other technical staff from each of the state and federal managing agencies to investigate water infrastructure and provide advice to governments, drillers and landholders on the most efficient and effective way to utilise new technologies for bore rehabilitation and bore drain replacement. Over more than two decades the work of the TWG was very effective in improving standards for bore drilling and maintenance, as well as for designing, installing and maintaining closed water delivery systems (National Uniform Drillers Licensing Committee, 2012). Closed water delivery systems deliver water to stock through well-maintained piped systems controlled by float valves in tanks and troughs to prevent leakage and waste of water. Agreed standards for water bores across the basin were established to reflect the range of conditions in which the bores were established, rehabilitated and maintained or abandoned. Government drillers and technical staff also provided a range of other services relative to the assessment of bores and delivery systems to landholders.

In each of the jurisdictions, governments offered different assistance packages to landholders who chose to install new water delivery infrastructure under the GABSI. Some included water plans for entire properties, negotiated between infrastructure engineers and landholders. For example, in some areas where bores were shared over several properties, water supply infrastructure was fully designed and supplied via external contracts and required the unanimous agreement of all landholders through bore trusts or other formal legal arrangements. Other packages offered landholder advice from engineers or consultants to assist in the design and installation of water delivery systems. However, some programs only assisted with bore rehabilitation, so landholders themselves designed and installed new water delivery infrastructure (Aurecon, 2009).

GABSI and allied programs were very important for employment in remote and regional areas. The rehabilitation of so many bores supported drillers, engineers and water infrastructure material suppliers. The steady supply of rehabilitation work justified maintaining government drilling crews and qualified contractors. This made it much easier and more economical for landholders to respond to maintenance issues and bore failures. Planners, water infrastructure engineers and installers in regional centres found steady employment.

New technologies and materials were developed and trialled by infrastructure supplier industries to address the problems identified during the transition to closed, piped systems. For example, closed water delivery systems create both benefits and challenges that did not exist with bore drains. High-temperature and high-pressure water from controlled bores demand the development and installation of new technologies, especially if landholders want to utilise natural pressure to push water around their property. The release of dissolved gases as piped pressure drops in piped systems causes blockages, which led to the development of a variety of in-line gas-release mechanisms with more or less effective outcomes.

High temperatures compromised the effectiveness and longevity of polypipe and required the installation of cooling grids until new materials and designs provided better solutions. Pipe size, quality fittings, valves, connectors, tanks and troughs, as well as innovation in installation, design and placement, all needed to be robust and 'fit for purpose', especially in the harsh environments in which they were installed (Aurecon, 2009).

As bore drains were replaced and systems extended to remote parts of properties, pastoralists faced new challenges for managing stock and grazing pressure and the management of infrastructure. In high-pressure areas of the GAB, well designed and installed distribution systems provide the opportunity to use artesian pressure to push water to remote watering points. In lower-pressure areas, or as pressure reduced in piped systems, a variety of different pumps including windmill, diesel and solar are used to push water around properties. Tanks with valves were often placed on high points so water gravity fed to troughs with controlled intakes. Some landholders let water flow into turkey nests and then pumped it to where it was required. Dispersed remote watering points required frequent 'bore runs', especially in hotter months. Bore runs often proved time consuming and expensive. As a result, the use of telemetry became widespread (James & Bubb, 2008).

These and many other factors meant that the costs and benefits, as well as the utility and reliability of water systems, were very different from those to which landholders were traditionally accustomed. The installation and features of the new piped water systems required technical understanding and advice to ensure acceptable outcomes. That support was not always available or sufficiently utilised. Infrastructure rehabilitation on some properties has been only partially completed under GABSI with, for example, only the rehabilitation of bores completed to date due to landholders being financially constrained, or the highest-flowing bores controlled but dribblers still remaining.

Pastoral Landholders

Changing from bore drains to closed water delivery systems was a massive shift in both lifestyle and business practice in the pastoral industry. At the beginning of the 18-year transition period, many landholders had no clear plan for the rehabilitation of uncontrolled bores and elimination of bore drains. All new bores were required to meet drilling standards and be fitted with headworks, but much of the water delivery infrastructure attached to bores fed into open bore drains or inefficient water delivery systems. The traditional practice favouring bore drains was strong, and some landholders were opposed to change; conversely, some adopters of new water distribution systems were passionate in advocating for change and the benefits available from this.

Participation in infrastructure rehabilitation was voluntary for most of the GABSI funding period. Government policy and regulations did not clearly define pastoralists' rights for taking stock water and their responsibilities to deliver water through closed delivery systems. As a result, the response by landholders (SKM, 2008) to the shared funding scheme under GABSI was mixed:

- Some landholders understood the benefits that would accrue from the GABSI funding arrangements. They recognised the need to restore pressure and save water, so installed and maintained closed water delivery systems. They influenced local cultures and encouraged fellow producers to adopt closed delivery systems. They accepted the responsibility for maintaining their water delivery infrastructure as an integral part of their business.
- Other landholders viewed GABSI incentives as just another opportunity for government assistance. They participated in the program but failed to change long-standing attitudes and water management practices. In the absence of clear enforceable regulation, they failed to install and maintain efficient delivery systems across their properties. Some of these landholders cite a lack of capacity to invest as the reason for poor maintenance. The response of this group compromises the desired outcomes of GABSI and puts at risk the public and private benefits from the investment.
- Some landholders, for a variety of reasons, still refuse to participate in bore and infrastructure rehabilitation or to change wasteful practices. Some do not have the capacity to

pay and still maintain a viable business. Dry periods and the fluctuations in commodity prices affect their capacity to invest. Others operate large, profitable grazing businesses but still refuse to change. Often these pastoral enterprises have non-resident owners with little understanding of or commitment to the GAB.

Despite this range in attitudes, landholders invested at least $50 million per GABSI phase as their part of the rehabilitation initiative, either as cash or in-kind activity. In addition, once landholders had converted to piped water delivery systems, they continued to invest many millions of dollars in pipes, tanks, fittings, pumps, and telemetry to extend water infrastructure beyond that serviced by bore drains into previously unwatered areas on their properties.

Over the life of the program, attitudes changed significantly from those that existed at the beginning of GABSI and continue to change (GABCC, 2011b). The numbers of landholders who advocate closed delivery systems is increasing, and only a minority are still holding out and maintaining wasteful practices. Some landholders require stronger incentives such as enforcement to comply, but most understand the need to adopt efficient practices.

Outcomes for the Basin

Between 1999 and 2018, over 250,000 ML of water was kept in the GAB for later generations by the control of almost 760 bores and the piping of most of the remaining bore drains (Table 4). While there is no doubt that the funding for GABSI has been the critical driver for the transition to more efficient and effective stock watering systems (Table 3), it certainly has not been the only key response during the transition period. The successful transition required a range of responses from critical interest groups including governments, landholders, the GABCC, State GAB Advisory Committees and water infrastructure suppliers. The outcomes driven by GABSI were realised only because of the range of complementary investments and programs delivered by governments and industries, and subsequent responses by the pastoral industry (Centre for International Economics, 2003; SKM, 2008).

Later government reviews of GABSI focus almost entirely on the single matrix of dollars per kilolitre saved, the number of bores rehabilitated and the length of bore drains closed (Tables 2 and 3) (Commonwealth Government, 2010; SKM, 2014). Although stock watering practices across the basin are much improved, the rehabilitation of artesian bores and closure of bore drains are not complete (Table 4). Issues surrounding the installation and ongoing maintenance of efficient stock watering practices across the basin have not disappeared. The nature of the GAB and the types of water delivery infrastructure mean that pastoral bores will continue to fail, and bores and stock watering systems will continue to require ongoing investment and maintenance (GABCC, 2013).

Table 4. Estimate of the remaining bore capping and piping work in the Great Artesian Basin (Department of Agriculture, Water and the Environment, 2020).

State	New South Wales	Queensland[3]	South Australia	Total
Bores to be controlled[1]	229	179	23	431
Bore drains to be deleted (km)[2]	1,150	3,896	0	5,136
Estimated water saving (ML/annum)[2]	26,600	89,296	365	116,261
Total estimated cost ($ million)[2]	114	135	1.25	250.25

[1] GABCC (2017). Summary of past drilling activity within the Great Artesian Basin – November 2017; updated to reflect projects completed since November 2017.

[2] SKM (2014). Great Artesian Basin Sustainability Initiative Value for Money Review – January 2014; these figures are estimates based on state data.

[3] (GHD, 2019). Census of uncontrolled artesian bores and artesian-fed bore drains in Queensland: Bore Summary Report.

Note: This table presents the known number of artesian flowing bores. All states have bores that have become subartesian, either due to declining head or due to discharge below the surface, that also require rehabilitation but are not currently counted (S. Cheal, pers. comm.).

A New Management Plan for the Basin

Responding to Changes in the Management Environment

The policy and management environment in the GAB changed extensively during the implementation of the 2000 SMP. The mid-term review of the SMP completed in 2007 detailed achievements during the implementation period and the challenges that still needed to be addressed (GABCC, 2009). In 2014, GABCC and the basin governments facilitated a two-day 'Futures Workshop' to update the findings of the mid-term review and focus on the need for a new SMP. As a result, governments and the GABCC proposed and agreed to a framework to develop a new strategic management plan in 2015.

Reviews concluded that a comprehensive, outcomes-based SMP was required. The review found that a plan would provide a basin-wide framework that complements national and state legislation. It should be developed around principles that protect the rights of current users and offer scope for development while protecting the resource and the cultural and natural values that it supports (GABCC, 2013).

Legislation and on-ground practices in each of the jurisdictions changed in response to challenges and opportunities over the implementation period of the 2000 SMP; however, the review emphasised that a range of management challenges remain. The judicious use of water by all users is accepted as the key management goal.

The GAB Strategic Management Plan 2019

The revised SMP is principle based and reflects the national water management guidelines and the new management environment, as well as the outcomes of the reviews. The Consultation Draft was released in mid-2018. Following the response to consultations, at the time of writing (late 2019) the final SMP was with Ministers awaiting release in the first quarter of 2020 (Department of Agriculture, Water and the Environment, 2020).

The SMP 2019 clearly identifies important challenges and opportunities that exist in the management of the GAB. Unfortunately, austerity budgets and changing priorities of governments mean that much of the technical, consultative and financial support that was so critical during the implementation of the 2000 SMP has been redirected. New data shows that there are more than 50,000 bores in the GAB (Table 5), with over 12,000 drilled before 1960 and at high risk of failure. There are 6600 artesian bores, and at least 430 bores remain uncontrolled. The estimated replacement cost for the artesian bores alone is $3.2 billion. Water from the basin supports more than $13 billion in production and supplies more than 120 towns (Frontier Economics, 2016). As well as their significant economic contribution, the residents in the basin have traditionally provided critical human and land management services across the more remote parts of three states. The Outback community continues in this important role today (Yelland & Brake, 2009).

Table 5. A summary of Great Artesian Basin bore statistics (GABCC, 2017).

50,496	Total number of bores drilled into and through the basin, including recharge and nonartesian areas; 75% of these are for water supply.
12,498	Number of bores drilled before 1960 and at high risk of failure; 1974 of these are in artesian or previously artesian areas, the majority being water supply bores.
676	Number of bores rehabilitated under the GABSI program since 2001.
14,000	Kilometres of bore drain replaced with piping under GABSI.
199,000	Estimated annual water saving (millions of litres) resulting from GABSI capping and piping.
658	Remaining bores with uncontrolled flow (at 2015); of these, about 516 (80%) were constructed prior to 1960.*
$4,351 million	Estimated replacement cost of all water supply bores.
$3,258 million	Estimated replacement cost of deeper, higher pressure water supply bores (excludes bores less than 200 m deep).

*Changes in flow in artesian bores as a result of capping programs are difficult to compile without comprehensive census. Many of these wells have small surface flows but may have flow loss below the surface.

GAB governance arrangements have changed considerably. There has been a move amongst regulators and politicians towards 'commodifying' water to move towards competitive pricing as the principal water management tool. Whether this is a desirable approach to regulating the waters of the GAB, with its remote location and sparse population along with its demography and industry mix, remains to be proven.

Summary and Conclusions

Access to water has been critical to the growth and establishment of the GAB pastoral industry for more than 120 years. The reduction in the potentiometric surface in response to water extraction practices was identified as the key groundwater management issue as early as 1905. For the first half of the 20th century, inadequate technology and limited understanding of the basin restricted responses by governments and landholders that may have helped address the problem.

Early on, landholders discovered that the best way to distribute water around their properties from uncontrolled bores was by constructing and maintaining bore drains and other open water delivery systems. These practices became firmly established in local landholder cultures. Government policy responses initially reinforced (or did not deter) such practices. Even as new technologies became available and were mandated for new bores, little was done to change or regulate established wasteful practices.

When governments recognised the need for change in the second half of the 20th century, landholders had little understanding of the benefits that might accrue from updating water delivery infrastructure and had few incentives to change. Flowing bores and wasteful practices in the GAB were not a high priority on the political agenda, so governments had few tools and resources to regulate use and improve management practices.

Shared funding initiatives, plus the wide range of supporting activities in each of the GAB jurisdictions from the 1970s through the 1990s, were invaluable in changing hearts and minds and raising uncontrolled GAB bores as a critical issue on the political agenda. GABSI was the stimulus required to accelerate and sustain the changes needed in the design and operation of stock water delivery systems. A national technical working group, passionate landholders, infrastructure designers and suppliers, government agency staff, researchers, the GABCC and state advisory groups worked cooperatively over the next two decades to ensure that GABSI was able to build on the initial successes.

The GABSI investment by governments and landholders was about $300 million over 18 years from 1999. Changes during the funding period were enabled by government policy development and reinforced by education and information initiatives that defined rights and responsibilities of water users and improved water management practices. With changes in water management practices in the pastoral industry, closed water delivery systems became the accepted best practice.

GABSI resulted in many benefits but also some less desirable unforeseen consequences. Comprehensive information exists concerning the critical role that governments, landholders and other interests assumed to support GABSI during each of the funding rounds; however, only simple metrics of dollars per kilolitre of water saved and the amount of infrastructure installed are reported as the key indicators in later and final GABSI audits. These simple metrics ignore some of the most important outputs and outcomes that have accrued during the transition period and beyond (Rolfe, 2010); no assessment is made of the returns on the investment made by governments and landholders to support GABSI. Changes were driven by GABSI but are a direct result of 18 years of well planned and executed cooperative initiatives between governments, landholders and others interested in productive, judicious use of the GAB.

According to Rolfe (2010), for any evaluation process to be comprehensive, it is important to include the assessment of values for the off-farm benefits, as these are likely to be the critical values that justify public investment. Off-farm benefits are largely public, accruing to different groups in society, and include recreation, tourism, ecological and biodiversity assets, including cultural heritage and options for future use and conservation, as well as reductions in greenhouse gases. In a 2010 benefit-transfer study, Rolfe (2010) estimated the off-farm benefits of improving the management of the GAB to be at least as high as $17.8 million per year, outweighing the annual program costs

of $15.5 million per year from the Australian and state governments in Stage 2 of the GABSI.

Rehabilitated bores, bore drains and public funds expended were audited at the end of each GABSI funding period. The audit of bores completed in 2018 shows that there are now more than 50,000 bores in the GAB, and the value of artesian water bores and water delivery infrastructure is in excess of $3.5 billion. There are still almost 2000 functioning artesian bores that were drilled before 1960. Bores will continue to fail, and water delivery infrastructure needs maintenance. Continuous investment will be required.

Lessons need to be learned from the past 120 years of GAB management (Smerdon, 2012). The future role of landholders and governments in the construction and management of water infrastructure is a major challenge identified in the new SMP. Although the report on final revision of GABSI clearly demonstrates that bore rehabilitation and compliance have been very successful, the move towards closed water delivery systems is not yet complete. If the true return on the investment is to be understood, reliable information on the broader inputs and outcomes of GABSI beyond just dollar cost of water saved needs to be investigated and added to information about the number of bores rehabilitated and bore drains closed. This information will provide the key evidence needed to guide future management and investment decisions concerning the taking of water from this valuable resource.

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Author Profile

Lynn Brake worked on natural resource management projects in the Outback of South Australia, Queensland and the Northern Territory for over 40 years. After moving from the US to South Australia in 1972, he secured a teaching and research position in natural resource policy and management at the University of South Australia. He retired from teaching in 1996. Lynn has served as a community bureaucrat on numerous boards, committees and councils dealing with water policy and management in Outback Australia. He was formerly the Presiding Member of the Arid Areas Catchment Water Management Board in South Australia, and a founding member of the Great Artesian Basin Consultative Council and the Lake Eyre Basin Community Advisory Committee. He held the Chair of the Water Advisory Committee for the South Australian Arid Lands Natural Resource Management Board and was the South Australian community representative on the Great Artesian Basin Coordinating Committee. He was a Patron of the Friends of Mound Springs.

Evaluating the Effectiveness of Fencing to Manage Feral Animal Impacts on High Conservation Value Artesian Spring Wetland Communities of Currawinya National Park

Stephen Peck[1]

Abstract

High levels of domestic and feral ungulate activity adversely affect the condition and extent of artesian spring wetlands in the Great Artesian Basin. It is essential that programs aimed at managing pest animal impacts on spring wetlands are correctly evaluated to determine their effectiveness. Species diversity, species detectability, condition and impact assessment tools were used to evaluate the effectiveness of exclusion fences. Biological and condition recovery were greatest under total pest animal exclusion. Partial exclusion was only marginally better than uncontrolled pest animal conditions. We found that evaluating management effectiveness of pest exclusion programs using targeted qualitative condition assessment tools is possible, allowing land managers to examine trends based on historical photo-monitoring.

Keywords: Eulo supergroup, Currawinya National Park, management effectiveness, exclusion fencing, qualitative condition class assessment, quantitative biological assessment

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Introduction

Artesian springs and their associated wetland communities are dependent on the discharge of groundwater from the Great Artesian Basin (GAB) (Queensland Wetland Program, 2005; Fairfax & Fensham, 2003; Ponder, 1986). These wetland communities are significant for their high levels of endemic flora and fauna, and their cultural and First Nations Peoples values (Davis et al., 2017; Powell et al., 2015; Fairfax & Fensham, 2003; Fairfax & Fensham, 2002; Robins, 1998). Individual springs have been grouped into 12 geographically clustered groups of springs referred to as 'supergroups' (Ponder, 1986, cited in Fairfax & Fensham, 2003).

The Budjiti Peoples have had a long and deep cultural connection with their Country, which includes Currawinya National Park. The Budjiti Peoples have managed the landscape for tens of thousands of years, which is highlighted by the abundance and diversity of both tangible and intangible cultural values. The Budjiti Peoples are known to have been using the springs of the Eulo supergroup for at least 13,000 years (QPWS, 2019a; Robins, 1998).

Early pastoralists quickly recognised the importance of springs as a reliable water source in a landscape with otherwise limited permanent surface water (Powell et al., 2015; Fensham et al., 2010). Over-utilisation of the GAB and individual spring groups has seen a significant decline in the condition and extent of artesian spring wetland communities (Fensham et al., 2004). Other threats to artesian springs include excavation for water storage, exotic plants, stock and feral animal disturbance, exotic aquatic animals, tourism and impoundment (Fensham et al., 2010).

Grazing by native species is a natural part of spring wetland ecology and can be essential for maintaining microhabitat and species diversity

(Fensham et al., 2010; Unmack & Minckley, 2008; Niejalke & Kovac, 2003). However, the permanent nature of springs in semi-arid and arid environments often means they support higher feral animal populations compared to adjacent waterless environment, especially during exceptionally dry periods (Negus et al., 2019; Russell et al., 2011; Fensham et al., 2010). Current levels of domestic and feral ungulate activity at some springs are adversely affecting the condition and extent of artesian spring wetland communities (Peck & D'Souza, unpublished data; Gotch, 2013; Fensham et al., 2010; Queensland Wetland Program, 2005; Niejalke & Kovac, 2003).

Rossini et al. (2017a,b) found that endemic gastropods were negatively impacted by desiccation, increased conductivity and the temperature of spring wetlands. Ground disturbance can lead to loss of microhabitats through the removal of the vegetation layers and other ground structures, increasing exposure and conductivity through the disturbance of salt-bearing soils. Snail kills involving hundreds of individuals have been reported from areas of intense pig rooting at Yowah Creek Springs (Peck & D'Souza, unpublished data).

Fencing is a commonly used tool to protect artesian springs from the impacts of stock and feral animals (Fensham et al., 2010; Niejalke & Kovac, 2003). However, fencing of artesian springs for management purposes can result in adverse and sometimes unpredictable outcomes for spring wetland communities and priority taxa (Davis et al., 2017; Fensham et al., 2010; Fensham et al., 2004). For example, total exclusion of all grazing through fencing can result in over-proliferation of native species such as the common reed (*Phragmites australis*) and *Fimbristylis* spp. (Davis et al., 2017; Fensham et al., 2010; Fensham et al., 2004). Increases in these species can result in increased direct competition, alterations to microhabitats, increased water transpiration and loss of areas of open water. These species are also palatable to stock and are selectively grazed; therefore, destocking can have a similar effect to exclusion fencing (Gotch, 2013).

Artesian spring wetlands have significant capacity for recovery when disturbance pressures are removed, which requires an adaptive management approach to achieve sustainable conservation outcomes (Peck & D'Souza, unpublished data; Fensham et al., 2010). Some monitoring programs are expensive, time consuming and require expert skills, but often the resources to support these requirements are limited. Evaluating the effectiveness of programs aimed at conserving the springs therefore requires the development of practical and easily implemented monitoring frameworks that require little additional resources and training (Hockings et al., 2006).

The aim of this research was to: (a) evaluate the management effectiveness of exclusion fences used to protect high conservation value artesian spring wetlands; and (b) compare the results from simple, qualitative condition class and impact assessments to those from a quantitative biological assessment program. This approach would determine the utility of the former qualitative assessment for evaluating the effectiveness of a management action designed to improve the condition of spring wetlands.

Materials and Methods

Study Site

The study was conducted between March 2011 and August 2017 at Currawinya National Park, in a semi-arid region of south-west Queensland (Figure 1). The study area experiences hot summers and mild winters with summer-dominant rainfall (Bureau of Meteorology, 2019). The average annual rainfall (295.5 mm) and total annual rainfall data for the years of the study were obtained from the Hungerford weather station (29.00°S, 144.41°E) (Figure 2).

Eight spring groups, including Massey, Tunga, Fish, Granite, Poached Egg, Basin Bore, Wetsoak and Yarraman, were fenced and monitored as part of the project. Massey and Tunga Springs are Category 1a springs, i.e. they contain at least one endemic species not known from any other springs (Fensham et al., 2010). The biological values of Massey Springs, including Little Massey Spring, are: *Jardinella eulo* – Endemic, no conservation status; *Eragrostis fenshamii* – Endangered; *Myriophyllum artesium* – Endangered; *Hydrocotyle dipleura* – Vulnerable; and disjunct populations of *Utricularia fenshamii* and *Utricularia caerulea* – Least concern. The biological values of Tunga Springs are: *Jardinella cf eulo* – Endemic, no conservation status; *Myriophyllum artesium* – Endangered; disjunct populations of *Schoenus falcatus* – Least concern; *Triglochin nana* – Least concern; *Utricularia fenshamii* and *Utricularia dichotoma* – Least

concern (Silcock et al., 2014; Jobson, 2013; Fensham et al., 2010; Ponder & Clark, 1990). Fish Springs and Poached Egg Spring are Category 2 springs, i.e. they provide habitat for populations of species not known from habitats other than spring wetlands within 250 km. Biological values include *Myriophyllum artesium* – Endangered; *Calocephalus glabratus* – Vulnerable; and *Utricularia fenshamii* – Least concern. Granite, Basin Bore, Wetsoak and Yarraman are Category 3 springs, i.e. they are intact springs without identified biological values (Jobson, 2013; Fensham et al., 2010).

Figure 1. Currawinya National Park, showing the location of Massey and Tunga spring groups (■) and other artesian springs (●).

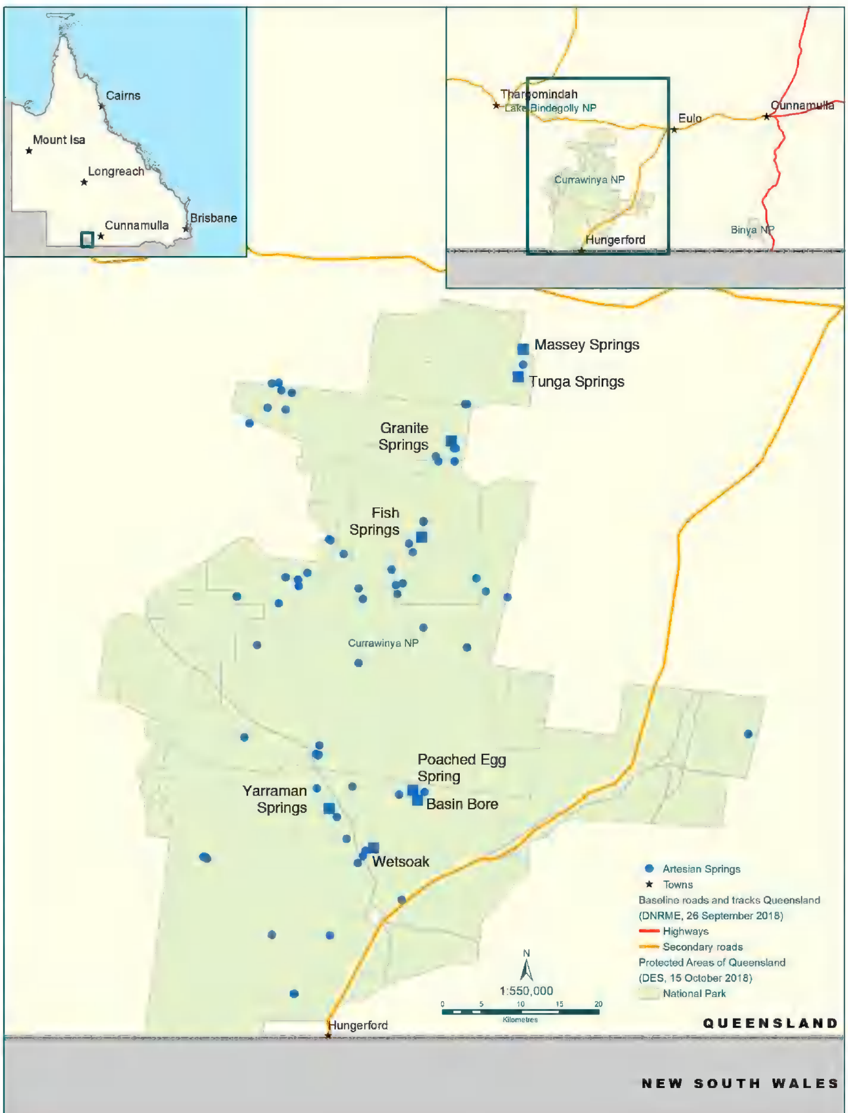
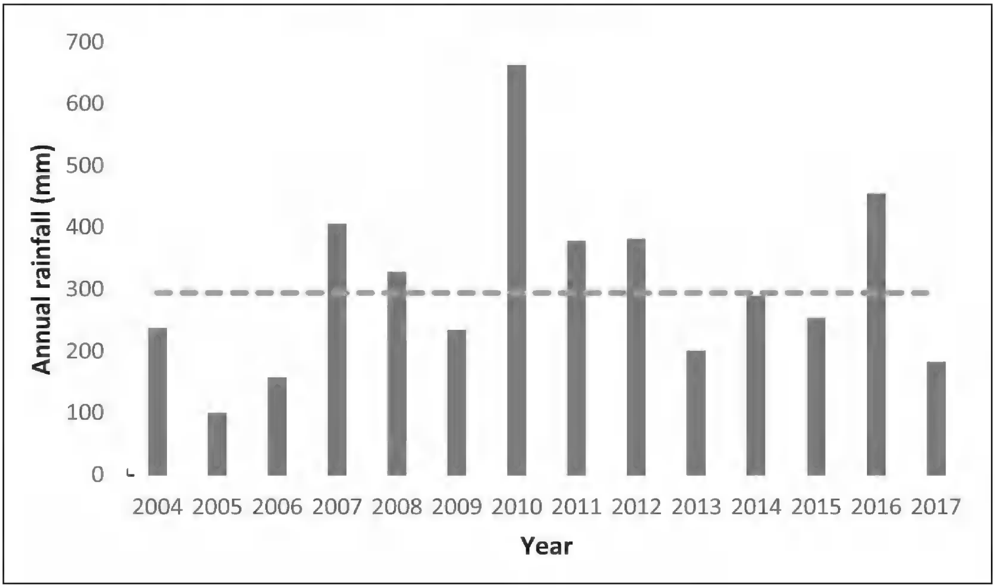


Figure 2. Annual rainfall recorded at the Hungerford weather station for the years 2005–2017. The dotted line represents average annual rainfall (Source: Bureau of Meteorology, 2019).



Prior to acquisition by Queensland Parks and Wildlife Service (QPWS) in 2012, Massey, Granite and Fish Springs were part of the Werewilka pastoral property, which included both Granite Springs and Werewilka properties. Massey Springs is located on the western slopes of the Hoods Range and is associated with a large granite seam that runs in a north-westerly direction from Hungerford (Queensland Parks and Wildlife Service and Partnerships, 2019a,b). Massey Springs appears to contain three main vents and intermittently runs a 600 m tail. A smaller vent (Little Massey) is located approximately 200 m south of the main spring group, between granite boulders and supporting a small, open pool of water (1 m^2) and a population of *Hydrocotyle dipleura* and *Myriophyllum artesium*. The Massey Springs group has a history of modifications. It has been delved (dug out) to improve water storage and stock access and was used for stock water as recently as 2014.

In 2012, QPWS acquired the Oolamon section of the Bingara pastoral property, which included Tunga Springs, located on the eastern slopes of Hoods Range, just below Mount Bingara. This spring group is located in the upper reaches of a stony drainage line within the Oolamon section of Bingara. There are numerous spring vents in a 0.5 ha area. Tunga Springs has a history of modification, with the remains of a bore head present and other infrastructure used to collect and store water. The old bore is uncapped, with a current flow rate of 0.5 L/min. In recent years there has been limited use of these springs by domestic stock.

Poached Egg, Basin Bore, Wetsoak and Yarraman Springs are all within the 1991 gazetted area of Currawinya National Park and are also within the Currawinya Lakes Ramsar area (Queensland Parks and Wildlife Service and Partnerships, 2019a,b).

Exclusion Fences

Eight spring groups were fenced between 2005 and 2015. The fence design for each site was determined by considering the topography of the site, soil type (rocks or sand), pest species involved, access, and cultural elements that may be associated with the spring site and adjacent areas. The initial Fish Springs fence was regularly compromised due to local ongoing flooding and was modified in 2012 to include three smaller mesh fences, vent 3, vent 9, and vents 4, 5, 6 and 7 (Table 1).

Table 1. Spring fence data, spring name, month and year fenced; type – mesh or wire; total area fenced (ha); total perimeter (m); material cost for mesh and wire fence; construction cost for mesh and wire fence; fence material cost = material cost × perimeter; fence construction cost = construction cost × perimeter; total cost = fence material cost + fence construction cost.

Spring	Fenced (month/ year)	Type	Area (ha)	Perimeter (m)	Material cost ($/km)	Construction cost ($/km)	Fence material cost ($)	Fence construction cost ($)	Total cost ($)
Tunga	Nov. 2013	Mesh	0.58	282	12,600	1,700	3,500	500	4,000
Fish (vent 3)	Apr. 2015	Mesh	0.015	50	12,600	1,700	600	100	700
Fish (vent 9)	Oct. 2013	Mesh	0.006	28	12,600	1,700	350	100	450
Massey	Jul. 2014	Wire	27.6	2015	6,700	2,500	13,500	5,000	18,500
Fish	Oct. 2011	Wire	8.2	1153	6,700	2,500	7,800	2,900	10,600
Fish (vents 4, 5, 6 & 7)	Apr. 2015	Wire	0.54	300	6,700	2,500	2,000	750	2,750
Granite	Apr. 2015	Wire	2.34	620	6,700	2,500	4,100	1,500	5,600
Basin Bore	Sep. 2012	Wire	147.4	4939	6,700	2,500	33,000	12,300	45,300
Yarraman	Jun. 2013	Wire	440.4	8774	6,700	2,500	58,700	22,000	80,700
Poached Egg	Oct. 2005	Wire	8.0	1100	6,700	2,500	7,300	2,700	10,000
Wetsoak	Sep. 2012	Wire	0.180	170	6,700	2,500	1,100	400	1,400

Two fence designs were used during this project. The 'wire' fence is a commonly used stock fence design. It consists of 9 × 90 hinge-joints with a single line of barbed wire at ground level, two mid-lines of high-tensile plain wire to support each hinge-joint, two top lines of barbed wire supported by a 1.8 m galvanised steel post every 6 metres, an inline strainer post every 500 m on spans of fence over 500 m in length, and a strainer post in all corners.

The 'mesh' consists of rigid 900-mm-high galvanised mesh with 75 × 100 mm aperture, a single line of barbed wire at ground level, two top lines of barbed wire supported by a 1.8 m galvanised steel post every 6 m, and a strainer post every 30 m. A 600 mm galvanised mesh apron was used in areas with uneven ground and was covered with logs and rocks to weigh the mesh down.

Qualitative Condition Class Assessment

Photographic monitoring was undertaken annually at each of the spring study sites. Photographs of Massey Springs, Tunga Springs, Fish Springs – vent 3, Fish Springs – vent 9 and Poached Egg Spring were then examined to determine a condition class (good, good with some concern, significant concern, critical) and associated impact score (4, 3, 2, 1, respectively) for the spring groups using three feral animal impact criteria (grazing, ground disturbance and water condition) (Table 2).

Quantitative Biological Assessment

Mean Plant Species Richness in the Ground Stratum

Plant species richness was determined for Massey and Tunga spring groups. Plant species richness along the vegetated edge of each spring was recorded using three 10 m × 2 m (area = 20 m^2) transects. The centre line of each transect was located approximately 1 m from the undisturbed edge of the spring vegetation and followed the shape of spring vegetation profile (typically nonlinear). This area is representative of the high level of ground disturbance as all animals accessing the spring must cross it.

Table 2. Grazing assessment criteria, impact score and condition class. Concept modified from QPWS Health Checks (Melzer, 2019) and the IUCN condition classes (Source: Hockings et al., 2006).

Condition class	Good	Good with some concern	Significant concern	Critical
Impact score	4	3	2	1
Grazing	No signs of grazing of wetland vegetation other than what would be expected by native animals; flowers and seed heads common and widespread.	Only minor signs of grazing in localised areas; flowers and seed heads common but with some signs of grazing.	Wetland vegetation lawn-like; flowers and seed heads restricted to protected areas (deep water or protected by logs and rocks).	Wetland vegetation mostly removed or absent; vegetation is present only in protected areas; flowers and seed heads not present.
Ground disturbance	No signs of physical ground disturbance other than what would be expected by native animals.	Only minor signs of ground disturbance (<25% ground disturbance).	Spring edge mostly disturbed or large areas of digging (26–75% ground disturbance).	Extensive ground disturbance, tubers and roots dug up and exposed; almost all vegetation impacted (>75% ground disturbance).
Water condition	No dung or dead animals; no signs of increased turbidity or fouling; no odour.	Limited amount of dung; localised signs of increased turbidity; fouling and odour.	Large amounts of dung or dead animals; increased turbidity; fouling and significant increase in odour.	Limited areas of open water; mostly reduced to a muddy slurry; water fouled by large amounts of dung or numerous dead animals; offensive odour.

The total numbers of individual species were recorded along each transect, and the mean plant species richness (total plant species ÷ 3) was then calculated for each spring group.

Indicator Species – *Jardinella* spp.

Two endemic gastropods from the genus *Jardinella* occur at Massey and Tunga Springs. Massey is the type locality for *J. eulo*, while a similar but distinct species, *J.* cf. *eulo*, occurs at Tunga Springs (Ponder, pers. comm., 22 February 2019). The presence of snails was recorded at each site against the following criteria: Not detected – no live snails were recorded; Scarce – restricted in their local distribution; and Abundant – live snails were found in the majority of locations searched.

Feral Animal Activity

Feral animal activity was recorded during all site visits and included species, numbers of each species, duration of presence at the spring, activity (grazing), water use (drinking), resting, rooting and wallowing.

Results

Fencing

Overall, exclusion fencing had a positive effect by reducing the impacts of domestic and feral ungulates on artesian spring wetlands. The 'mesh' exclusion fences, area <0.6 ha (range 0.006–0.58 ha), perimeter ≤282 m (range 28–282 m) were more effective at excluding target animals compared to the 'wire' exclusion fences, area >0.18 ha (range 0.18–440.4 ha) and perimeter >170 m (range 170–8774 m) (Table 1).

While 'wire' exclusion fences were effective at reducing domestic and feral ungulate access to the springs, they were also more likely to be compromised by feral animals either digging or pushing under the fence or pushing through the hinge-joint material, compared to the mesh fence. However, feral animal activity inside the 'wire' exclusion fences was lower than that recorded pre-fencing. Neither fence design restricted macropod access to the springs. The tail from the Tunga bore head flows through the fence creating a small water point just outside the fence. This significantly

reduced animal pressure on the fence, enhancing the effectiveness of the mesh fence at this site (Peck & D'Souza, unpublished data).

Wire fences were more likely to be negatively impacted by intense localised surface water flow events, causing a build-up of flood debris and soil erosion under the fence. The Fish Springs fence was completely removed due to ongoing flood damage and replaced with three separate mesh-fenced areas. Wire fences were more likely to be breached by feral animals either jumping or digging under the fence. The effort required to detect and remove feral animals from inside an exclusion fence increases with increasing size of the fenced area.

The total cost for the wire fence was $9,200.00/km; construction cost was $2,500.00/km (range $1,500.00–$3,500.00 depending on site) plus materials at $6,700.00/km. The total cost for the mesh fence was $14,300.00/km; construction cost was $1,700.00/km plus materials at $12,600.00/km. The average mesh fence perimeter was 120 m (range 0.028–0.282 km), area 0.2 ha (range 0.006–0.58 ha). The average wire fence was 2.38 km (range 0.170–8.774 km), area 79.33 ha (range 0.18–440.4 ha). The total cost per ha protected by mesh fences was $8,570.00 compared to wire fences at $275.00/ha.

Qualitative Condition Class Assessment

Massey Springs

In 2005, the spring vegetation was heavily grazed, with high levels of ground disturbance and poor water quality (Figure 3A). In 2011, following above-average rainfall and prior to fencing, the condition of the springs improved considerably (Figure 3B). In 2013, the springs showed signs of feral and macropod grazing (Figure 3C). Figure 3D shows the springs in the first year, post-fencing; the springs still show signs of grazing, predominantly by macropods.

Figure 3. Massey Springs: (A) 2005 (unfenced), impact score 1, condition class 'Critical'; (B) 2011 (unfenced), impact score 4, condition class 'Good'; (C) 2013 (unfenced), impact score 2.7, condition class 'Significant concern'; (D) 2015 (fenced), impact score 2.7, condition class 'Significant concern'.

Tunga Springs

Tunga Springs was in a very poor condition in 2012 (unfenced), with substantial grazing, ground disturbance and poor water quality, predominantly due to high feral goat and moderate pig activity (Peck, pers. obs) (Figure 4A). Post-fencing wetland vegetation recovery is shown in Figures 4B, C and D.

Fish Springs – Vent 3

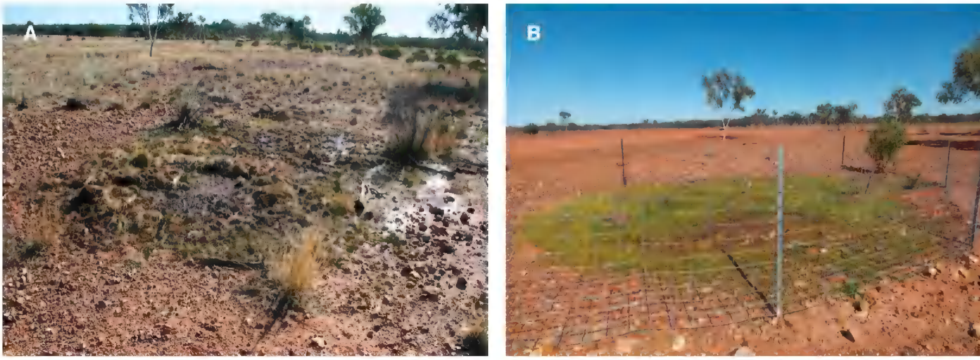
In 2011, the spring vegetation was heavily grazed, with high levels of ground disturbance and poor water quality. Prior to 2011, this spring was often completely turned over by pigs and was in a highly degraded condition (Peck, pers. obs). In 2012, the spring was fenced and the condition of the spring improved markedly. However, the fence was frequently compromised by local flood damage between 2012 and 2015, resulting in ongoing feral animal access and impact on the spring. In 2015, a mesh fence was constructed, restricting feral animal access to the spring while still allowing macropod access. *Utricularia fenshamii* had not been recorded (flowering) at Fish Springs prior to the construction of the mesh fence in 2015, but is now considered abundant. The absence of flowers in other years was most likely the result of preferential and ongoing grazing. In 2017, the height of the fence was increased, further restricting macropod access to the spring. The spring condition improved markedly despite below-average rainfall.

Fish Springs – Vent 9

In 2011, the spring vegetation was heavily grazed, with high levels of ground disturbance and poor water quality (Figure 5A). The condition of the spring improved in 2012 on the back of several years of above-average rainfall before declining in 2013–2014. In 2014, a mesh fence was constructed, restricting feral animal access to the spring while still allowing macropod access. The condition of the spring improved markedly despite several years of below-average rainfall (Figure 5B).

Figure 4. Tunga Springs: (A) 2012 (unfenced), impact score 1, condition class 'Critical'; (B) 2013 (fenced), impact score 2, condition class 'Significant concern'; (C) 2014 (fenced), impact score 3.7, condition class 'Good with some concern'; (D) 2015 (fenced), impact score 4, condition class 'Good'.

Figure 5. Fish Springs – vent 9: (A) 2012 (unfenced), impact score 1, condition class 'Critical, pig damage'; (B) 2016 (fenced), impact score 4, condition class 'Good'.



Poached Egg Spring

Poached Egg Spring is an unvegetated-water spring. Prior to 2005 it was highly impacted by feral horses, removing the adjacent vegetation (shrub and ground cover) and reducing the springs to a muddy bog (Peck, pers. obs) (Figure 6A). Recovery of the springs and adjacent areas was slow post-fencing in 2005. However, the condition improved markedly in 2010, mostly as a result of above-average rainfall in that year (Figure 6B). *Calocephalus glabratus* is an endemic daisy from the Eulo supergroup. It is a palatable species and suffers from over-grazing. Once scarce at Poached Egg Spring, this population has recovered post-fencing and is now considered to be the single largest population of this vulnerable species (Silcock et al., 2014).

Feral Animal Impact Assessment

There was considerable variation in the results of the condition class assessment for Massey Springs. In 2005 (pre-fencing), Massey Springs' assessment score was 1 for grazing and water quality and 2 for ground disturbance, giving an average of 1.3. The condition class was deemed to be 'Critical'. In 2011 and 2012 (pre-fencing), the assessment score was 4 for all three assessment criteria, with an overall average of 4. The condition class was deemed to be 'Good'. Between 2013 and 2017, the average impact assessment score range was 2.7–3. The condition class was considered to be of 'Significant concern' (Table 3). After fencing, ground disturbance and water conditions stabilised while grazing impacts were increased.

Figure 6. Poached Egg Spring: (A) 2005 (unfenced), impact score 1, condition class 'Critical'; (B) 2012 (fenced), impact score 4, condition class 'Good, above-average rainfall'.

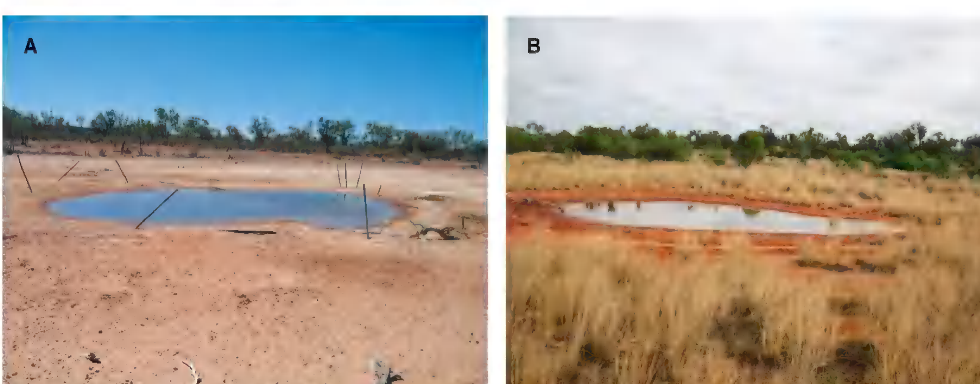


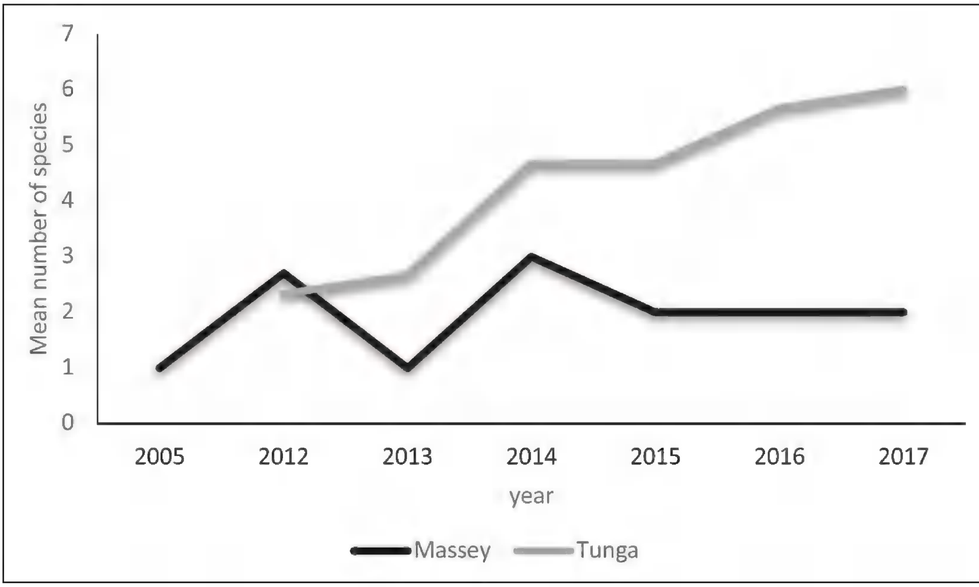
Table 3. Impact assessment and condition class for Massey Springs, Tunga Springs, Fish – vent 3, Fish – vent 9, and Poached Egg Spring. Animal impacts on vegetation (grazing), ground condition (pugging and rooting) and water quality (turbidity and odour) were scored between 1 and 4. Legend: 1 – Highly impacted; 2 – Mostly impacted; 3 – Minor impact; and 4 – No impact. Condition classes are linked to impact scores: Good; Good with some concern; Significant concern; and Critical.

Spring	Year	Grazing	Ground condition	Water quality	Average impact score and condition class
Massey	2005	1	2	1	1.3
	2011	4	4	4	4
	2012	4	4	4	4
	2013	2	3	3	2.7
	2014*	3	3	3	3
	2015*	2	3	4	3
	2016*	2	3	4	3
	2017*	2	3	4	3
Tunga	2012	1	1	1	1
	2013*	2	2	2	2
	2014*	3	4	4	3.7
	2015*	4	4	4	4
	2016*	4	4	4	4
	2017*	4	4	4	4
Fish – vent 3	2011†	1	1	1	1
	2012†	4	4	4	4
	2013†	2	2	2	2
	2014†	4	4	4	4
	2015*	4	4	4	4
	2016*	3	4	4	3.7
	2017*	4	4	4	4
Fish – vent 9	2011†	1	1	1	1
	2012†	3	3	3	3
	2013†	1	1	2	1.3
	2014*	1	1	1	1
	2015*	4	4	4	4
	2016*	4	4	4	4
	2017*	4	4	4	4
Poached Egg	1999	1	1	1	1
	2005*	1	1	1	1
	2006*	1	2	3	2
	2007*	1	2	2	1.7
	2008*	2	2	2	2
	2009*	3	3	3	3
	2010*	4	4	4	4
	2011*	4	4	4	4
	2012*	4	4	4	4
	2013*	4	4	4	4
	2014*	4	4	4	4
	2015*	4	4	4	4
	2016*	4	4	4	4
	2017*	4	4	4	4

* Year the spring group was fenced.

† Year the individual spring was fenced but fence was flood damaged.

Figure 7. Mean plant species richness in the ground disturbance zone. Tunga Springs was fenced in November 2013 and Massey Springs in July 2014. *Note*: 2005–2006, 2009, 2013–2015 and 2017 were years of below-average rainfall.



The average impact scores for Tunga Springs in 2012 and 2013, prior to fencing, were 1 and 2 with a condition class of 'Critical' and 'Significant concern', respectively. Post-fencing in 2013, the average condition assessment scores increased to 3.7, 4, 4 and 4 for 2014, 2015, 2016 and 2017, respectively. The overall condition class was 'Good' (Table 3).

Prior to fencing in 2011, the condition of Fish – vent 3 was 1 – 'Critical'. The condition has continued to improve post-2013, with an impact score and condition class range of 3.7 ('Some concern') to 4 ('Good'). Prior to the construction of the mesh fence at Fish – vent 9 in 2014, the condition class and impact score remained low. Following the construction of the mesh fence in 2014, the condition of the spring improved and has remained 'Good' for several years (Table 3).

The Poached Egg Spring impact scores remained low between 2005 and 2008: ranges 1 ('Critical') and 2 ('Significant concern'). There was gradual improvement recorded between 2008 and 2009. The condition class was deemed to be 4 ('Good') in 2010 and has remained that way since (Table 3).

Quantitative Biological Assessment

Mean Plant Species Richness

Mean plant species richness was lowest at both Massey and Tunga spring groups prior to fencing. Mean plant species richness increased throughout the monitoring period for both sites (Figure 7). Massey Springs had a lower mean plant species richness (range: 1–3 species) compared to Tunga Springs (range: 2.33–6 species).

Indicator Species

Snails were not detected at Massey Springs or were scarce in six out of the eight years (75%) and abundant in two consecutive years (25%) (Table 4). Snails were not detected at Tunga Springs for the first four years (66.7%) and were scarce in 2016. In 2017, snails were abundant at Tunga Springs and were recorded from five vents, including the bore and tail and three central vents with limited connectivity with each other, and one small vent that is >10 m from the nearest vent with snails (Table 4). In 2013, this vent had a small pool of water with <2 m^2 of wetland vegetation consisting of grazed *Cyperus laevigatus*. Snails were absent

from both sites when pest animal impact was high and unmanaged.

Feral Animal Activity

Goats and pigs were present at all spring sites, with either animals sighted or evidence such as tracks, fresh dung, wallows and rooting recorded on all visits. Feral animal activity appeared to be influenced by rainfall, with higher activity recorded during below-average or average rainfall years compared to lower activity during above-average rainfall years. Small numbers (2–10) of wild horses were recorded at Poached Egg, Basin Bore, Wetsoak, Yarraman and Fish Springs. Large numbers of feral goats (>300/day) and feral pigs (2–10/day) were recorded at Massey Springs. Tunga Springs also supported large numbers of feral goats (>200/day) and pigs (2–10). Goat activity was short in duration, usually less than 1 hour per visit and typically involved watering and grazing on spring vegetation. It was not possible to determine whether individual goats made multiple visits in a single day. Pigs, pig wallows and rooting were recorded at all spring sites. Pig activity was long in duration, with camera trap data indicating that some individual pigs are semi-permanent spring residents.

Discussion

Pest animal exclusion fencing is a practical and effective management tool for protecting wetland areas of high conservation value, especially in situations where baiting, shooting and mustering fail to provide sustainable outcomes (Negus et al., 2019; Peck & D'Souza, unpublished data; Clapperton & Day, 2001). However, fencing as a management tool is not cheap and requires significant ongoing maintenance to remain effective (Negus et al., 2019).

Mesh fences are more effective at excluding feral animals from small areas compared to wire fences. The cost of constructing a mesh fence is relatively high compared to the cost of wire fences; however, the cost difference is offset by mesh fences being smaller and better suited to protecting individual springs or small spring groups that are not suitable for the wire fence option. One common complaint about mesh fences is their impact on the aesthetic values of the area, as they are usually located relatively close to the spring wetland and therefore are readily seen.

While the main objective of this program was the protection of the artesian springs of the Eulo supergroup, it could be argued that wire fences were less effective and therefore mesh fences are a better option. However, regardless of the design, the condition of the fenced springs was better than their unfenced state. The lower cost of wire fences makes them suitable for fencing larger areas, and therefore land managers could consider wire fences for protecting springs and other landscape values associated with the springs, such as the First Nation Peoples' cultural values.

Table 4. Detectability of *Jardinella* species: NT – Not Detected, S – Scarce, and A – Abundant; mean impact score and condition class, with 1 – Highly impacted, 2 – Mostly impacted, 3 – Minor impact, and 4 – No impact. Condition classes are linked to impact scores ■ Good, ■ Good with some concern, ■ Significant concern, and ■ Critical for Massey and Tunga spring groups between 2005 and 2017. Annual rainfall data for Hungerford weather station showing if the year was: below average – Below; above average – Above; and average – Average (annual average = 295.5 mm).

	2005	2011	2012	2013	2014	2015	2016	2017
Annual total rainfall	Below	Above	Above	Below	Average	Below	Above	Below
Massey Snail detectability	NT	A	A	S	S	NT	S	NT
Massey Mean impact score	1.3	4	4	2.7	3*	2.7*	2.7*	2.7*
Tunga Snail detectability	—	—	NT	NT	NT	NT	S	A
Tunga Mean impact score	—	—	1	2*	3.7*	4*	4*	4*

* Year the spring group was fenced.

For example, the Yarraman Springs fence protects a total area of 440.4 ha, which includes only a few low-value springs with at least one mound spring containing mega-fauna remains. However, the fence protects a large Budjiti Peoples cultural area identified during the pre-fencing cultural clearance survey from ongoing pest animal disturbance.

Densities of domestic and feral ungulates and several species of kangaroo have increased throughout arid Australia through the increase of artificial watering points (Fensham & Fairfax, 2008). Previous research has shown that the impacts from domestic stock, including grazing and ground disturbance, have a negative impact on spring wetlands, reducing species diversity (Rossini et al., 2017a,b; Gotch, 2013; Kovac & Mackay, 2009; Niejalke & Kovac, 2003).

The results of this study show that species diversity along the vegetated edge of spring wetlands and snail detectability were lowest during periods of high, uncontrolled feral animal activity. While the initial recovery happened quickly, plant species richness is still increasing four years after total feral animal exclusion at Tunga Springs, and even when feral animal activity was reduced at Massey, it had not stabilised over a three-year period. The abundance of the amphibious gastropods *J. eulo* and *J.* cf. *eulo* appears to be negatively correlated with increased levels of feral animal disturbance of the spring wetlands, especially in areas of shallow clear water. The results of this study support the results of other research that domestic and feral animals do negatively impact artesian spring wetland communities, especially during years of below-average rainfall (Davis et al., 2017; Peck & D'Souza, unpublished data; Gotch, 2013; Fensham et al., 2010; Unmack & Minckley, 2008; Niejalke & Kovac, 2003).

The results of this study show that artesian spring wetlands communities have significant capacity for recovery when disturbance pressures are removed. The condition and impact assessment results for Massey (2011, 2012) and Fish (2012) Springs indicated that the springs were in 'Good' condition despite not being fenced. These years corresponded with years of above-average rainfall. In these wetter years, feral and native species disperse across the landscape in response to improved food and water availability, and feral animal activity and impacts at the springs are reduced (Peck, pers. obs).

Evaluating the effectiveness of management actions is an essential part of good protected area management. Evaluating management effectiveness is vital at local, regional and national levels to ensure targeted management actions are meeting their intended goals (Hockings et al., 2006). Queensland Parks and Wildlife Service and Partnerships has an obligation under their management instruments (management plans) to ensure the protection of areas recognised for their significant natural values. While management decisions need to be based on scientific evidence, practical monitoring tools are required to allow protected area management staff to undertake routine monitoring of complex natural systems. The results of this study show that there was a strong relationship between the condition class and impact assessment scores and the biological assessment results, indicating that the qualitative condition assessment described here is an efficient tool for evaluating management effectiveness.

The results of this study indicate that feral animal activity can be managed effectively through appropriately designed exclusion fences, and that when feral animal activity is well managed, artesian spring wetland communities have a considerable capacity for recovery. Small mesh fences are more effective at protecting individual or small groups of springs, while large wire fence designs may be more appropriate when broader aesthetic, cultural and other environmental values require protection. The results show that evaluating management effectiveness can be achieved using appropriately designed qualitative assessment tools. The benefit of these qualitative tools is that they are easier for local management staff to use, interpret and present results on a routine basis, potentially providing early-warning signals of changes that require quantitative ecological assessment.

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Author Profile

Stephen Peck works for the Queensland Parks and Wildlife Service and Partnerships and was the Natural Resource Ranger – South-West region for 14 years. He has had a long-term, hands-on approach to the management and conservation of the GAB springs of the Eulo, Bourke and Springvale supergroups. His main area of interest is monitoring the springs and reducing the impact of feral animals on the cultural, natural and visitor values of these unique environments. He fenced his first spring in 2003 and is still activity involved in spring management.

Decadal Changes in *Phragmites australis* Performance in Lake Eyre Supergroup Spring Communities Following Stock Exclusion

Simon Lewis[1], and Jasmin G. Packer[2,3]

Abstract

Many ecosystems around the world are vulnerable to competitive expansion by cosmopolitan colonisers (e.g. *Phragmites australis*, common reed) where human-mediated disturbance increases nutrient levels. Yet our understanding of the long-term dynamics within vegetation communities once this disturbance has been excluded, and how best to reduce the residual negative effects, is limited. The Great Artesian Basin (GAB) springs in South Australia offer a useful case study of vegetation responses post-disturbance because they form a collection of semi-independent ecosystems with a rich management history, from burning by Aboriginal people to pastoralism and stock exclusion from some springs since the 1980s. This paper presents a case study based on 35 years of observational data on the response of *P. australis* and other wetland vegetation at protected GAB springs of the Lake Eyre supergroup. The case study aims to understand how naturally present *P. australis* performs within GAB spring communities following stock exclusion. Where *P. australis* was present at the time of stock exclusion, it became monodominant across the main pool of several springs within the first decade, and expanded throughout the spring tail during the second and third decades. The endangered salt pipewort (*Eriocaulon carsonii*) appears to have been reduced in distribution and abundance where *P. australis* became monodominant. However, in two promising cases, *P. australis* dominance waned after 30+ years of stock exclusion and, in another, has not colonised a spring free of *P. australis* at the time of de-stocking despite the presence of source populations in a neighbouring spring. These findings suggest that decadal cycles of above-ground dominance followed by decline may occur in some GAB springs where *P. australis* was present at the time of stock exclusion. Active management of *P. australis* may be required, particularly where its dominant expansion phase poses a threat to species of conservation significance.

Keywords: Great Artesian Basin springs, conservation and management, pastoral lands, *Phragmites australis*, endangered species

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Introduction

Human-mediated disturbance is reducing the heterogeneity and biodiversity of natural ecosystems around the world (Winter et al., 2009; Aronson et al., 2014). Pastoral settlement is a widespread example of this. Many dryland vegetation communities are heavily impacted by domestic stock (e.g. cattle, *Bos taurus*, or sheep, *Ovis aries*), pest animals and occasionally over-abundant native herbivores. The impacts of their combined grazing pressure (e.g. soil compaction, nutrient enrichment, changes in species composition and abundance, reduced vegetation complexity) are most concentrated around watering points such as troughs and wetlands (Johnes et al., 1996; Landsberg et al., 2002). To reduce these negative effects on wetland communities within landscapes dominated by dryland pastoralism, many have been fenced to

exclude stock and other herbivores over the past 40 years (e.g. Dobkin et al., 1998; Yates et al., 2000). The long-term effects of stock removal on wetland vegetation communities within dryland regions, however, are poorly understood.

Phragmites australis is a tall-statured grass species native to Australia but with a cosmopolitan distribution, forming monodominant stands in many wetlands throughout temperate and dryland regions of the world (Kobbing et al., 2013; Packer et al., 2017; Canavan et al., 2019). As a woody perennial grass, *P. australis* provides important reedbed habitat for native bird (Tmka et al., 2014; Kane, 2001; Kiviat, 2013), insect (Tscharntke, 1999) and mammal species (Kiviat, 2013), and is an important coloniser in the hydroseral succession from aquatic to terrestrial habitats for plant communities (Packer et al., 2017). This broad ecological envelope, together with a tall-statured lifeform, gives it an advantage as one of the most invasive plants in the world (Canavan et al., 2019; Kueffer et al., 2013). *Phragmites australis* competitiveness is closely linked with its ability to persist and thrive in a variety of hydrological (water levels and flow regimes; Deegan et al., 2007; Gotch, 2013) and nutrient (Packer et al., in review) conditions. *Phragmites australis* is also a very important component of many traditional and semi-traditional socioeconomic systems and practices around the world, including its use since prehistoric times for roof thatching (e.g. Kobbing et al., 2013).

Mechanisms for *Phragmites* reproduction vary in form and success. *Phragmites* can reproduce vegetatively (clonal expansion by rhizomes, or by dispersal of rhizomes or stems by water or animals; Meyerson et al., 2014; Packer et al., 2017) or sexually via seedling recruitment (Kettenring & Wigham, 2009; Kettenring et al., 2011). Water, wind and, to a lesser extent, fauna such as birds disperse the small and light seeds of *Phragmites* (Kiviat, 2013; Packer et al., 2017). Although established *Phragmites* stands are able to expand into many areas, including those with previous ecological disturbance (Moore, 1973; Roberts, 2016; Duffield & Roberts, 2016), germination and seedling establishment are limited as *Phragmites* seeds require particular environmental conditions (Greenwood & MacFarlane, 2006; Gotch, 2013). The few reported cases of new populations established from seed in Australia have been where it has colonised muddy flats through to shallow, still water ±10 cm above ground level (Packer et al., 2017). The expansion of dense monodominant *Phragmites* has been associated with reduced floristic diversity within some freshwater wetland areas, particularly where the *Phragmites* has colonised as non-native stands (e.g. Hazelton et al., 2014). The three main characteristics that make *Phragmites* an effective competitor are rhizomatous growth and aeration, shoot height and shoot density (Gotch, 2013; Canavan et al., 2019). Direct competition is through space occupancy and shading, and shorter plants are often outcompeted.

Within Australia, *Phragmites australis* is the most common member of the genus, and natural populations are found in many parts of eastern Australia through to Tasmania (Roberts, 2000; Duffield & Roberts, 2016; Packer et al., 2017). Within South Australia, it occurs in dryland (e.g. Great Artesian Basin springs, River Murray corridor) through to temperate (e.g. Fleurieu Peninsula swamps) climate zones.

The Great Artesian Basin (GAB) is the largest groundwater basin in Australia and one of the largest in the world. It covers 22% of the Australian continent, including areas in Queensland, New South Wales (NSW), South Australia and the Northern Territory. Great Artesian Basin groundwater supports an estimated 7000 individual springs in 450 spring groups scattered across the basin. Two species of *Phragmites* occur in the Great Artesian Basin springs – *P. karka* and *P. australis*. For the most part, this paper is concerned with *P. australis* as one of the most important wetland species internationally and in the Great Artesian Basin springs, and the term *Phragmites* is used hereon.

Phragmites occurs as a natural component in many springs across the GAB. The GAB springs are of enormous cultural significance to Indigenous people, being their only reliable water source in the region for thousands of years. Archaeology in and around spring sites reflects the importance of these permanent water sources in the otherwise dry landscapes (Hercus & Sutton, 1985; Harris, 2002). There is evidence of traditional burning of *Phragmites* stands by Aboriginal people, as well as excavation of areas with *Phragmites* to improve access to water (Hercus & Sutton, 1985).

Disturbance of spring vegetation associated with

European settlement dates from the mid-1800s. Soon after exploration of South Australia's Far North, commencing in the late 1850s, pastoralism was introduced to the region. Pastoralism at Anna Creek Station, for example, dates back to 1863 (Harris, 2002). In the earliest days of pastoralism, the GAB springs provided the only reliable water resource in the region, and many springs were fenced by pastoralists to maintain a clean water supply and prevent bogging of stock. However, from the late 1870s, artesian bores were drilled and these became the main watering points for stock. As a result, most of the early fencing around springs was not maintained. A large number of GAB springs have therefore been subject to pressure from stock and other herbivores for over 130 years.

Within the Great Artesian Basin, exclusion of stock and other introduced herbivores from some wetlands already containing *Phragmites* has led to its expansion and reduced floristic richness of other native spring vegetation (Fensham et al., 2004; Davies et al., 2010; Gotch, 2013). However, the relationship between *Phragmites* and reduced plant diversity is not always straightforward. Invasion and spread of *Phragmites* may not result in reduced diversity if other plants are competitive and capable of out-shading *Phragmites* (Buttery et al., 1965; Keller, 2000), or produce biomass earlier in the annual growth cycle (Gussewell & Edwards, 1999). The performance of *Phragmites* also depends on the genotype(s) present, with some *Phragmites* genotypes being more able to thrive in particular conditions (e.g. substrate types) than others (Packer et al., 2017; Saltonstall, 2002). The substrate conditions in which *Phragmites* contributes to wetland diversity rather than monodominance are presently unclear for the Great Artesian Basin mound springs and many other wetlands within dryland regions.

To investigate the response of *P. australis* to exclusion of stock and other introduced herbivores around permanent artesian-fed springs of the Great Artesian Basin, this paper presents a case study with 35 years of observational data on the Lake Eyre supergroup of mound springs in South Australia. The case study aims to understand how naturally present *Phragmites* populations expand and perform within vegetation communities of GAB springs following stock exclusion. To achieve this aim, three core questions were investigated:

1. How does the performance of *Phragmites* (above-ground distribution and coverage) respond to exclusion of stock grazing, and how has this changed over the past 35 years?
2. How does distance to nearest neighbouring springs influence the colonisation of *Phragmites* at hitherto *Phragmites*-free springs?
3. What trends in spring vegetation composition are evident where *Phragmites* has become dominant across this spring group and timescale?

These insights are important to inform management of the community of native species dependent upon natural discharge of groundwater from the GAB – declared as an endangered ecological community under the *Commonwealth Environment Protection and Biodiversity Conservation Act 1999.*

Materials and Methods

Study System

This case study focused on the natural springs of the Great Artesian Basin in the vicinity of Kati Thanda–Lake Eyre, often described as the Lake Eyre spring supergroup (Figure 1). Within this spring supergroup, approximately 3800 spring vents over many hundreds of springs have been described (Lewis et al., 2013). Here 'vent' is defined as a single discharge of artesian water at the land surface and 'spring' as the total wetland associated with a vent, or one or more immediately adjacent vents. In many instances, a single 'spring' often comprises several spring vents.

Case Study Springs

The case study focuses on 12 springs fenced to exclude stock and other herbivores, and a large number of springs, described as Finniss Springs, on the former Finniss Springs pastoral lease, now managed by the Arabana Aboriginal Corporation and de-stocked in the mid-1980s (Table 1). The first 10 springs listed in Table 1 were fenced by the South Australian Department of Environment and Planning in the 1980s and were, at that time, on actively grazed pastoral lease land. The fencing comprised timber posts with four strands of barbed wire, predominantly to exclude stock (cattle) as well as donkeys and horses – both present in the area.

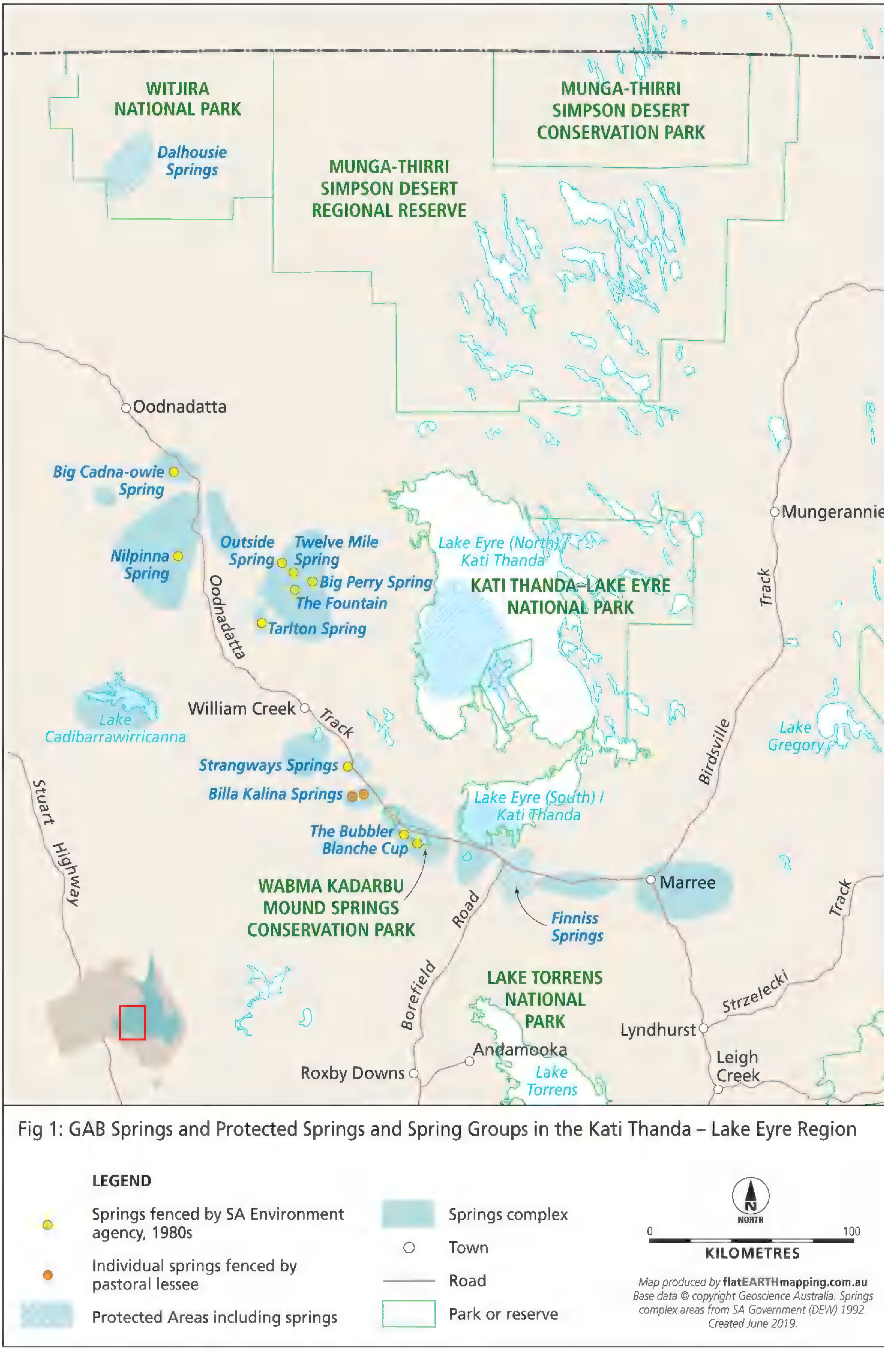
Other potential pest species – such as camels and wild pigs – do not occur in the area to any significant extent, and native macropods are very sparse. *Phragmites* was naturally present at Big Perry, The Fountain, Twelve Mile, Outside, Nilpinna and Big Cadna-owie Springs, but absent from Blanche Cup, the Bubbler, Tarlton and the selected Strangways spring. This coordinated fencing program, and the long-term monitoring of responses, has been one of the major conservation investments for the region's Great Artesian Basin springs. Two springs on Billa Kalina pastoral lease are also included in this case study; these were fenced by the pastoral lessee in the early 2000s – again following a long history of cattle grazing. These springs are less than 100 m apart: one had *Phragmites* fringing a pool at the time of fencing while, at the second, there was no *Phragmites*. The springs on Finniss Springs Aboriginal lands were de-stocked in the mid-1980s, although some horses remain on the property. The Finniss Springs group includes several hundred springs around Hermit Hill (Hermit, Finniss and West Finniss Springs), with several others in the near vicinity to the south (e.g. Bopeechee, Beatrice, Venables). In terms of spring vegetation, Hermit and West Finniss Springs are most noteworthy for the occurrence of salt pipewort (*Eriocaulon carsonii*), an endangered endemic species limited to just a few sites in two spring supergroups in South Australia (Lake Eyre and Lake Frome supergroups). It also occurs at a small number of spring sites in Queensland and NSW (Davies et al., 2010). The vast majority of springs in the Finniss Springs group have *Phragmites*.

Table 1. Case study springs protected from grazing animals since 1980s.

Spring/s	Location	Area protected (ha)*	Year	*Phragmites* presence/absence	Other predominant wetland plant species
Blanche Cup	Then Stuart Creek Pastoral Lease (P.L.), now Wabma Kadarbu Mound Springs Conservation Park	1.0	1984	Absent	*Cyperus laevigatus*
The Bubbler	As above	6.3	1984	Absent	*C. laevigatus*, *Schoenoplectus litoralis*
Strangways spring	Anna Creek P.L.	0.1	1984	Absent	*C. laevigatus*, *C. gymnocaulos*
Big Perry	Peake P.L.	2.7	1986	Present	*Typha domingensis*, *C. laevigatus*, *C. gymnocaulos*, *Juncus kraussii*
The Fountain	Peake P.L.	0.7	1986	Present	*C. laevigatus*, *C. gymnocaulos*
Twelve Mile	Peake P.L.	2.6	1986	Present	*C. gymnocaulos*, *T. domingensis*
Outside	Peake P.L.	0.4	1986	Present	*C. laevigatus*, *C. gymnocaulos*
Tarlton†	Peake P.L.	9.2	1986	Absent	*C. laevigatus*, *T. domingensis*
Old Nilpinna	Nilpinna P.L.	4.0	1986	Present	*C. laevigatus*, *C. gymnocaulos*
Big Cadna-owie	Allandale P.L.	0.2	1986	Present	*C. laevigatus*, *C. gymnocaulos*
Billa Kalina Springs	Billa Kalina P.L.	~3.0	ca 2001	Present, spring 1; absent, spring 2	Spring 2: *C. laevigatus*, *C. gymnocaulos*
Finniss Springs	Finniss Springs Aboriginal Lands	Entire property, approx. 800 springs	ca 1985	Generally present	Predominantly *C. laevigatus* but with other sedges including *Juncus*, *Baumea*, *Schoenoplectus* and *Gahnia*

* All but Finniss Springs fenced with timber posts and four strands of barbed wire, primarily to exclude cattle, donkeys and horses.
† Tarlton Spring subsequently determined to be fed from local groundwater, not GAB.

Figure 1. GAB springs and protected springs and spring groups in the Kati Thanda–Lake Eyre region.



Measuring the Performance of *Phragmites australis*

The case study incorporates published and unpublished literature on *Phragmites* performance and management in the Lake Eyre supergroup. Qualitative data on plant communities within the 10 springs fenced by the South Australian Department of Environment and Planning in the mid-1980s were derived from photo-point monitoring records collected by the Department (1984–2005) before and after fencing. The Department established a total of 66 photo-points across the 10 springs. From 2005, the volunteer group Friends of Mound Springs (FOMS) has maintained some of the photo-points on an opportunistic basis (1–3 yearly). However, many of the original photo-points have become overgrown by *Phragmites*, and FOMS volunteers have reverted to more general observations and photographs to assess trends. At Finniss Springs and Billa Kalina pastoral lease, qualitative vegetation data were obtained from regular (1–2 yearly) site-specific observations and analysis of changes and trends by FOMS from 2006 to the present.

Soil nutrient levels and *Phragmites* productivity have been surveyed at several GAB mound springs in South Australia, including one of the case study springs – Bopeechee Spring within Finniss Springs. As with the other GAB springs in the Finniss Springs group, Bopeechee Spring has been free of stock pressure since the mid-1980s and has become dominated by *Phragmites*. Bopeechee Spring was selected for a burning trial in 2016. Prior to the burn, soil nutrients and *Phragmites* productivity were recorded. The density, height and survival (proportion aborted) of *Phragmites* stems were recorded in fifteen 1 × 1 m quadrats in June 2016.

Results

Monitoring and general observations at the 10 springs fenced by the South Australian Department of Environment and Planning in the 1980s have shown no change in the presence or absence of *Phragmites* at individual springs. This stability has also been noted through qualitative observations at the de-stocked springs on Finniss Springs Aboriginal lands and two fenced springs on Billa Kalina pastoral lease. The results presented here are therefore described under two categories:

- Springs without *Phragmites* at time of stock exclusion.
- Springs with Phragmites at time of stock exclusion.

Springs without *Phragmites* at Time of Stock Exclusion

Blanche Cup and the Bubbler

Wetland structure and floristic composition at Blanche Cup (Figure 2A) and the Bubbler (Figure 2B) changed relatively little in the 35 years since these springs have been protected from stock grazing. Both springs continue to have an open pool fringed by bore-drain sedge (*Cyperus laevigatus*) and a wetland tail of plant species that includes *C. laevigatus* and, in the case of the Bubbler's extensive wetland outflowing tail, a diversity of other aquatic species including shore club-rush (*Schoenoplectus litoralis*) and fringing native myrtle (*Myoporum montanum*).

Both Blanche Cup and the Bubbler are within 100 metres or less of other springs and seeps that contain *Phragmites*, but there has been no sign of colonisation by this species at either spring. A point of interest is that both Blanche Cup and the Bubbler are subject to heavy visitation as feature springs within the Wabma Kadarbu Mound Springs Conservation Park. At both springs there has been significant trampling of *C. laevigatus* around the open pools, a situation that prompted the construction of boardwalks by the SA National Parks and Wildlife Service approximately 10 years ago.

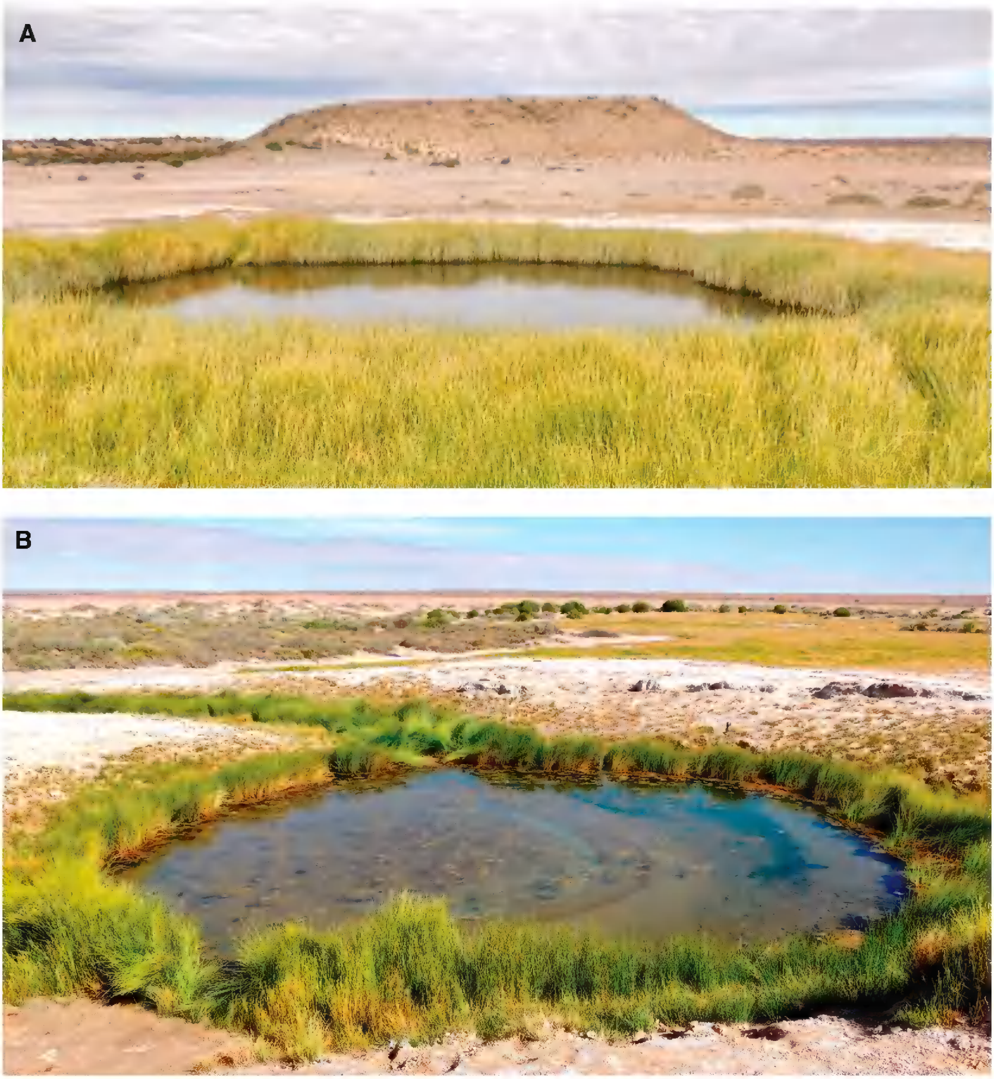
It is relevant to note that another spring close to Blanche Cup and the Bubbler – Little Bubbler (not included in the original fencing program but subsequently protected within the Wabma Kadarbu Mound Springs Conservation Park) – was, until the early 2000s, free of *Phragmites*. Its vegetation comprised almost entirely *C. laevigatus*. In the early 2000s, *Phragmites* was noted at the spring vent. Since that time, *Phragmites* has spread very gradually to occupy about five square metres at the Little Bubbler vent. This is the only recorded incidence of *Phragmites* colonising a previously *Phragmites*-free spring in the Lake Eyre spring supergroup.

Strangways Spring

The Strangways spring, fenced as part of the 1980s program, has remained free of *Phragmites*.

Its wetland vegetation is dominated by *C. laevigatus*, with some spiny flat-sedge (*Cyperus gymnocaulos*) and brown-head samphire (*Halosarcia indica*). The Strangways spring is approximately 500 metres from the nearest spring that contains *Phragmites*. While there have been no flow measurements at this fenced spring, visual observations have shown the outflow down the spring tail has diminished. During the 1980s and 1990s, the spring flow extended along the tail and through the protective fencing, but now the spring tail is dry well within the fenced area. This is consistent with observations at the other active springs (approximately 80) in the Strangways Springs group.

Figure 2. (A) Blanche Cup Spring with fringing bore-drain sedge (*Cyperus laevigatus*), no *Phragmites*, and extinct mound spring Hamilton Hill in the background; (B) The Bubbler vent and extensive tail with vegetation dominated by *C. laevigatus*, but no *Phragmites*.



Tarlton Spring

Tarlton Spring is an individual spring that is not now regarded as a GAB spring but as one tapping into more localised aquifers. However, the response of the native bulrush (*Typha domingensis*) to stock exclusion is relevant to this study of GAB springs. At the time of fencing in the mid-1980s, the three main spring vents at Tarlton Spring each had a small patch of *Typha* with spring tails dominated by the bore-drain sedge (*C. laevigatus*). The response to stock exclusion was rapid proliferation of *Typha* down the spring tails, similar to the pattern of invasion by *Phragmites*, with *C. laevigatus* reduced to a narrow fringe of growth. Tarlton is a very isolated spring, and *Phragmites* has remained absent. In recent years the vents at Tarlton have virtually dried up, reflecting the effects of seasonal variations in the local aquifers.

Billa Kalina Spring

One of the two springs fenced by the Billa Kalina lessees in the early 2000s has remained free of *Phragmites*, despite being within 100 metres of the other fenced spring which has abundant *Phragmites*.

Springs with Phragmites at Time of Stock Exclusion

Springs Fenced by the South Australian Environment Agency in 1980s

At the springs that included *Phragmites* at the time of protection in the 1980s (Big Perry, The Fountain, Twelve Mile, Outside, Nilpinna and Big Cadna-owie), substantial changes followed the fencing. At the time of fencing, the majority of these springs comprised open pools fringed by a mix of *C. laevigatus* and *Phragmites*, along with a low diversity of other wetland species such as the sedge *Cyperus gymnocaulos*. Figure 3A provides a typical example of this situation at Big Cadna-owie Spring. The first noticeable change was the relatively rapid and dense growth of *Phragmites* over the first five years post-fencing. Within about five years, rapid and dense growth of *Phragmites* expanded over the main spring vents, leaving no pools of open water (Figure 3B).

In a somewhat slower process, exemplified by The Fountain Spring, *Phragmites* expanded more slowly down the spring tail, hitherto dominated by the bore-drain sedge (*C. laevigatus*). After approximately 20 years of stock exclusion, further changes occurred at The Fountain and Outside Springs (Figure 4). Since the early 2000s there has been a steady decline in the above-ground growth of *Phragmites* in the main vents at the two springs – to the extent that areas of open water have been emerging since 2017.

At the other fenced springs containing *Phragmites* (Big Perry, Twelve Mile, Nilpinna and Big Cadna-owie), the dominance of *Phragmites* has continued after the early proliferation immediately following fencing. No open pools are present at these springs. Table 2 provides an overview of vegetation trends at the 10 springs following fencing, while Figures 3A and 3B show the then-and-now situation at Big Cadna-owie Spring.

De-stocked Springs on Finniss Springs Aboriginal Lands

At Finniss Springs, where most of the springs contain *Phragmites*, regular observations following stock exclusion in the mid-1980s showed a trend similar to the springs fenced in the 1980s (Figure 5), as referred to above. Prior to stock exclusion (early 1990s), *Phragmites* was largely restricted to spring vents, surrounded by an extensive halo of *C. laevigatus* and other sedges. Several years after stock exclusion (late 1990s–early 2000s), *Phragmites* growth extended out, with the sedge haloes much reduced. Nearly three decades after stock exclusion (2019), *Phragmites* extended over virtually the whole wetland area, with *C. laevigatus* sedge haloes further reduced or no longer present at several springs.

Springs within the Finniss Springs group, specifically Hermit and West Finniss Springs, provide habitat for the endangered salt pipewort, *Eriocaulon carsonii* (Figure 6). Qualitative observations have shown a reduced incidence of *E. carsonii* at these springs, associated with the proliferation of *Phragmites*.

Soil chemistry, nutrient levels and *Phragmites* stem response have been surveyed at one of the springs on Finniss Springs – Bopeechee Spring (Table 3). The figures are not highly informative as a single sampling but are indicative of data that would be useful if collected more widely and systematically to establish relationships between *Phragmites* performance, nutrient levels and soil chemistry.

Figure 3. (A) Big Cadna-owie Spring, Allandale Station, 1983 prior to fencing, with *Phragmites*, *C. laevigatus* and some open water areas present; (B) Big Cadna-owie, 2013, dominated by *Phragmites*.

Figure 4. Vegetation sequence at Outside Spring before and after stock exclusion.

>100 years: 1860s–1970s
Pastoralism

1978: Open water with mixed vegetation community, including *Phragmites*.

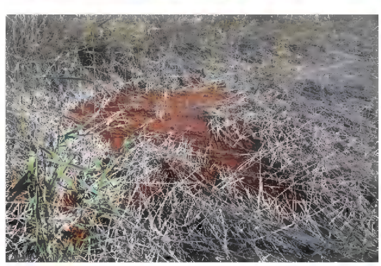
1980s–1990s
(10 years after stock exclusion)
Phragmites dominance

1999: With complete cover of *Phragmites*.

2000–2010
(20–25 years exclusion)
Phragmites senescing

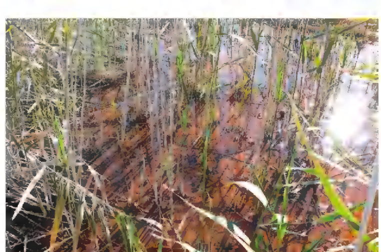
2008: *Phragmites* in centre of vent senescing and matting down.

2010–2015
(25–30 years exclusion)
Open water re-emerging



2014: Continued senescence of *Phragmites* in main vent area.

2015–2020
(>30 yrs exclusion)
Open water dominance



2016: *Phragmites* in vent declining in above-water cover and areas of open water re-emerging.

Figure 5. Vegetation sequence at Finniss Springs following de-stocking.

1985
Recently de-stocked

Phragmites present at vents (olive-green, middle ground) but surrounded by large haloes of sedges (foreground). The endangered salt pipewort occurred commonly on the inner (damper) edges of the haloes.

2007
Spreading *Phragmites*

The *Phragmites* is spreading into the haloes of sedges (shorter wispy *Phragmites* surrounding the taller original clump).

2015
Dominant *Phragmites*

Phragmites has spread to the outer edges of the spring wetlands to dominate the whole wetland area.

Figure 6. Endangered salt pipewort (*Eriocaulon carsonii*) amongst *Phragmites* at Hermit Hill Spring, Finniss Springs group, 2015.

Billa Kalina Spring

In the spring where *Phragmites* was present at the time of fencing, it has proliferated to dominate the entire spring. The neighbouring fenced spring, less than 100 metres away and free of *Phragmites* at the time of fencing, remains free of *Phragmites* (Figure 7).

Figure 7. Adjoining springs at Billa Kalina fenced in early 2000s, photographed in 2017: (A) with dense stands of *Phragmites*; (B) with no *Phragmites*. Wetland vegetation comprises *Cyperus gymnocaulos* surrounded by samphire species.

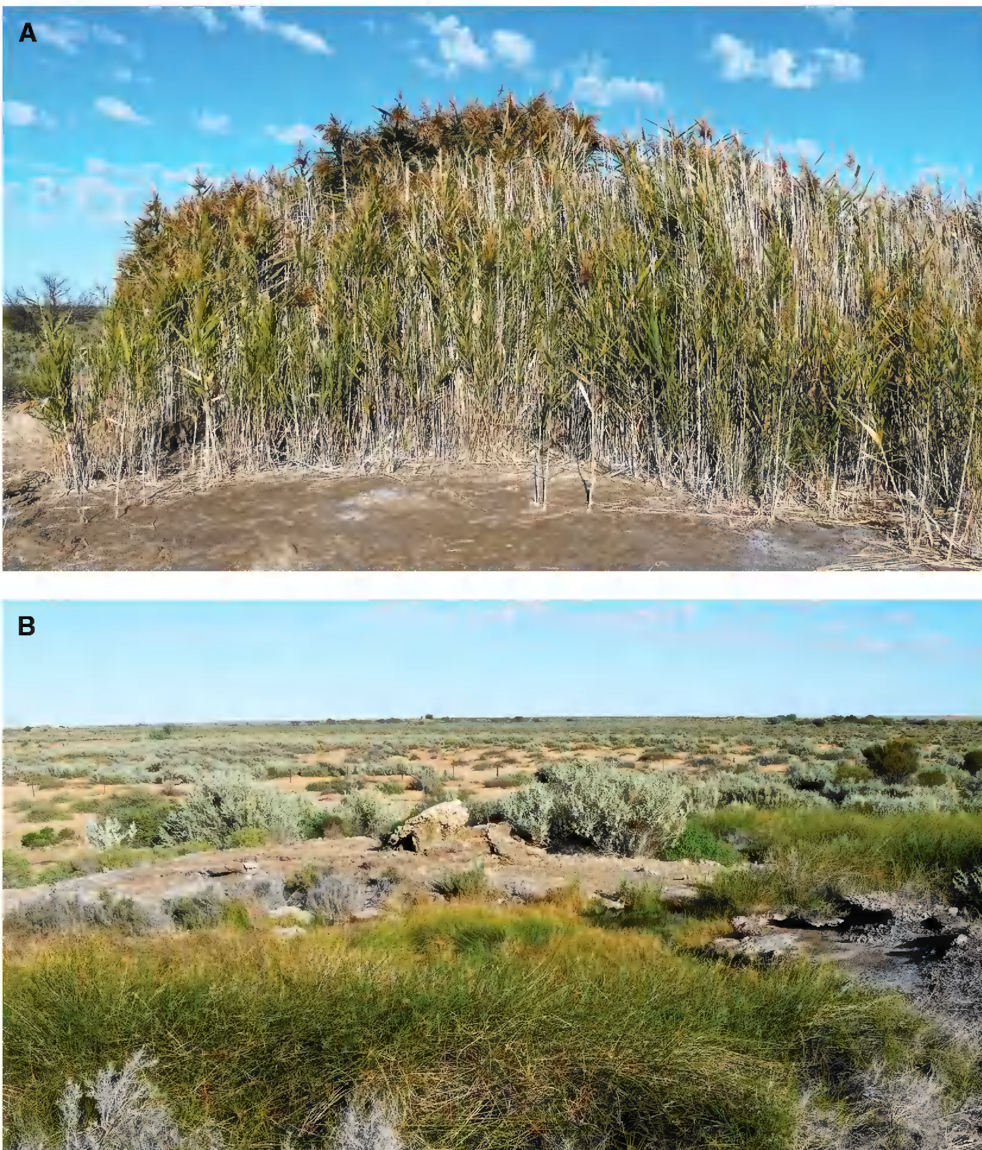


Table 2. Indicative timeline for vegetation changes in Lake Eyre supergroup springs containing *Phragmites australis*, fenced or de-stocked in the 1980s.

Mid-1980s before fencing	Mid-1990s 10 years after fencing	Early 2000s 20 years after fencing	2019 30+ years after fencing
Open pools fringed by *Phragmites*, interspersed with *Cyperus laevigatus*. Spring tails dominated by *C. laevigatus*.	Spring vents totally overgrown with *Phragmites*, no open water. Spring tails still mainly *C. laevigatus* but *Phragmites* starting to colonise towards the tail.	Vents still totally overgrown with *Phragmites*. Spring tails now dominated by *Phragmites* with small fringing areas of *C. laevigatus*.	Some vents showing significantly reduced *Phragmites* and some open water, majority still overgrown. Spring tails still dominated by *Phragmites*.

Table 3. Soil chemistry, nutrient levels and *Phragmites australis* stem response at Bopeechee Spring, Finniss Springs. Data recorded in 1 × 1 m quadrats in June 2016.

	pH	Salinity (ppm)	Nitrate NO_3 (mg/kg)	Ammonium NH_4 (mg/kg)	Phosphorus P (mg/Kg)	Stems Total	Stem Maximum length (mm)
Mean (SE)	7.74 (0.10)	1120 (77)	<1.0	<1.0	—	22.6 (3.3)	4062 (285)
Minimum	7.29	758	<1.0	<1.0	5.0	4	3050
Maximum	8.37	1518	2.1	2.1	6.0	38	5280

Discussion

Within South Australia, the majority of GAB springs occur on pastoral lease land used predominantly for cattle production over the last 120–150 years (Lewis & Harris, 2020). Stock and pest animals have a direct impact on spring vegetation and can lead to the loss of plant species, as well as causing pugging and increased nutrient levels (nitrates and phosphates) in spring waters and sediments, thereby affecting habitat quality. There are concerns that there have been associated losses of endemic flora and fauna (Fatchen & Fatchen, 1993; Kovac & Mackay, 2009).

Techniques to prevent damage from stock and pest animals include exclusion fencing around springs and de-stocking of spring areas. However, in protected areas that contain *Phragmites*, this has resulted in *Phragmites* expansion which excludes other spring vegetation and reduces open-water habitat. Findings of this case study within the Lake Eyre supergroup support previous reports of *Phragmites* as an effective and rapid expander in disturbed springs within the Great Artesian Basin (Fensham et al., 2004; Davies et al., 2010; Gotch, 2013). *Phragmites australis* has flourished in the changing post-disturbance hydrological and habitat conditions around spring vents and expanded into spring tails. These findings highlight the implications for springs and their flora when they are protected from stock and other herbivores after a long history of grazing.

The main findings in relation to the three key questions on *Phragmites* performance within Lake Eyre supergroup springs that have been protected since the mid-1980s are discussed below.

Performance of *Phragmites* in GAB Springs Following Exclusion of Stock Grazing

The response of spring vegetation communities to stock exclusion was striking and occurred within 5–10 years. At springs where *Phragmites* was present at the time of stock exclusion, there was a relatively rapid proliferation of *Phragmites* – initially at the spring vent in the first 10 years or so following stock exclusion, then spreading into most of the spring tail over the following 10–20 years.

The monodominant expansion of *Phragmites* in GAB springs following cessation of grazing pressure is unsurprising and consistent with its post-disturbance performance elsewhere in Australia (Roberts, 2000; Duffield & Roberts, 2016) and beyond (Hürlimann, 1951; Caffrey & Beglin, 1996; Packer et al., 2017). *Phragmites australis* occurs naturally in many of the springs of the Lake Eyre supergroup and in many other GAB springs. It has been present at Warburton Spring

in the Lake Eyre supergroup for over 30,000 years (Gotch, 2013). In all of the case study springs where *Phragmites* has proliferated, it was already present at the time of fencing and stock exclusion.

The case study has also provided important indications of decadal changes in *Phragmites* density within springs protected for over 30 years. In particular, vegetation observation at Outside Spring and The Fountain indicate that above-ground growth of *Phragmites* is diminishing in the main pool. Vegetation succession may be occurring within these protected spring communities: from vegetation-fringed open pools, to complete vegetation cover, and more recently towards *Phragmites* decline and open-water, vegetation-fringed pools again. These observations indicate that, in the longer term, protected springs may sometimes revert to a vegetation community with reduced above-ground *Phragmites*.

Phragmites often has a competitive advantage where it occurs in disturbed sites and where the main source of disturbance – such as stock grazing – has been removed. Less clear, however, is whether, and if so how, physical or chemical conditions might also interact with disturbance and *Phragmites* performance. In particular, many of the case study springs were previously grazed for a century or more prior to exclusion, so nutrient levels in spring sediments are likely to have increased substantially. *Phragmites* is known to thrive in nutrient-rich conditions (Duffield & Roberts, 2016; Packer et al., in review). The apparent relationships between *Phragmites* density, height and cover, nutrient levels and other aspects of sediment and water quality in GAB springs require further investigation.

Potential for Establishment of *Phragmites* at Hitherto *Phragmites*-free Springs

Although *Phragmites* is common in many spring vents and seeps within Wabma Kadarbu Mound Springs Conservation Park, it has not established at Blanche Cup or the Bubbler. Similarly, at Billa Kalina, there has been no establishment of *Phragmites* at a fenced *Phragmites*-free spring despite its close proximity to a spring with *Phragmites* within the same exclosure. These examples support observations elsewhere (Gotch, 2013) that there is a low probability of colonisation into *Phragmites*-free springs within the Lake Eyre supergroup. In the single recorded case of *Phragmites* establishment at a previously *Phragmites*-free spring in this spring group – the Little Bubbler – its rate of spread has been slow, suggesting that there may be abiotic conditions at the Little Bubbler not conducive to rapid spread.

Impacts of *Phragmites* Proliferation on the Composition of Spring Vegetation

Within the GAB springs, there is evidence of reduced floristic richness in wetlands where *Phragmites* has proliferated (Fensham et al., 2004; Davies et al., 2010; Gotch, 2013). Observations at the recently protected Lake Eyre case study springs tend to support this. Observations and vegetation photopoint monitoring have shown that the distribution and abundance of other spring-dependent plant species are being significantly reduced. At several springs, the formerly common and often dominant bore-drain sedge (*C. laevigatus*) has been reduced in distribution and abundance, while other sedges such as *Baumea* and *Bolboschoenus* have also reduced in abundance. The occurrence and possibly the abundance of endangered salt pipewort (*Eriocaulon carsonii*) at the GAB springs at Hermit Hill (Hermit and West Finniss Springs) have apparently declined. Observations in the early 2000s showed *E. carsonii* at several springs, whereas in 2015 just one occurrence was identified despite a comprehensive search (FOMS, 2015). This supports other findings that the proliferation of *Phragmites* can take over the habitat formerly occupied by *E. carsonii* (e.g. SA Arid Lands NRM Board, 2010).

Implications for Conservation and Management

Historically, one of the cornerstones of conservation of native plant and animal communities has been exclusion of impacts by stock and other introduced animals, and this approach has been applied to GAB springs. For springs without *Phragmites* – and possibly other tall macrophytes such as *Typha* – this appears to be a reasonable strategy. However, the proliferation and dominance of *Phragmites* in springs containing *Phragmites* at the time of stock and other animal exclusion does raise questions about the management of those springs.

In broad terms, the two main options following exclusion of stock and other herbivores are: (a) do

nothing on the assumption that *Phragmites* dominance will eventually decline, leading to increased abundance of other wetland plant species and possibly even the re-establishment of open-water pools; or (b) apply an active management regime to reduce the dominance of *Phragmites* and promote the retention or restoration of more diverse wetland communities.

The case study presented in this paper provides information about the results stemming from the 'do nothing' option over a timeframe of up to 35 years. In two cases out of six amongst *Phragmites* springs fenced in the mid-1980s, there was eventually a reduction in density of above-ground *Phragmites* over 30+ years. In the remaining four cases, *Phragmites* continues to be dominant and it is not at all clear whether its density will eventually follow the same trend. If *Phragmites* growth is responding to elevated nutrient levels following more than a century of stock access, then a decline may eventually occur, but the likely timing of this is unclear and more research is needed into the relationships between *Phragmites* proliferation and elevated nutrient levels. A broad, coordinated program to measure the parameters presented in Table 3 would be a useful start in assessing these relationships.

The need for active management of GAB springs with prolific *Phragmites* becomes more relevant where that proliferation may impact upon other wetland species that are of particular conservation significance. The observational evidence suggesting a reduction in distribution and abundance of the endangered *E. carsonii* at Finniss Springs is an example of this. Where species of particular conservation significance are involved, there may be a case for active reduction of *Phragmites* – in effect to hasten the cycle through to reduced incidence and density of this species. According to the hypothesis that *Phragmites* responds to elevated nutrient levels post-grazing, active management could hasten the reduction in nutrient levels and thus the reduction in *Phragmites* monodominance.

Active management to reduce *Phragmites*, where it is considered overabundant or invasive, has included slashing, burning, cutting, grazing, and herbicide application (Keller, 2000; Saltonstall, 2002; Sun et al., 2007). In general, these treatments were found to have only short-term effects and limited feasibility for scaling up to the extent needed (Sun et al., 2007). The use of fire or other techniques to remove above-ground biomass of *Phragmites* is recommended during summer or early autumn when the nutrient content of their shoots is greatest, thus inflicting physiological stress (Hellings & Gallagher, 1992; Güsewell, 2003). Several studies have highlighted the role of controlled or pulse stock grazing in reducing *Phragmites* growth (e.g. Coates et al., 2010). From observations in GAB springs over several decades, it is clear that grazing by cattle can reduce the biomass of *Phragmites* substantially. Pulse grazing will, however, also add a further infusion of nutrients to the spring environment, which may prolong the cycle of vigorous *Phragmites* growth.

A further method with potential to reduce *Phragmites* dominance and hasten the decline in GAB spring nutrient levels is slashing the above-ground *Phragmites* biomass to protect and promote the growth of threatened plants (e.g. *E. carsonii*) (J. Packer, unpublished data). *Phragmites* is often used in phytoremediation because it is an efficient remover of nutrients and heavy metals (Tanner et al., 2006). Removing the cut biomass could therefore help to reduce nutrient levels in the spring community. While the after-use of harvested thatch is unlikely to be a practical option in remote springs country, trials using this method at selected springs could be considered. As a single management event, either burning or slashing is not likely to have a lasting effect for *Phragmites* management. A long-term commitment to repeated interventions over many years is likely to be necessary.

Future Directions to Address Conservation Knowledge and Management Gaps

Our case study findings and related literature suggest that elevated nutrient levels in spring substrates, following more than a century of stock disturbance and grazing, may be an important factor in promoting prolific regrowth of *Phragmites* following stock exclusion. Further research is required to monitor nutrient levels directly and test our prediction of their influence on *Phragmites* performance. We suggest two GAB spring groups where this prediction could be tested: (1) the 12 fenced case-study springs described in this paper, where protected springs can be compared with nearby unfenced springs; and

(2) Hawker Springs where a large spring group is subject to various levels of stock pressure.

Hawker Springs, on the Peake pastoral lease, comprises up to 100 spring vents in a relatively tight grouping. Observations by FOMS volunteers and others suggest that the outer springs in this group are most frequented by stock, while the inner springs are much less impacted. This is a very suitable spring group for a coordinated study of grazing impacts, trends in nutrient levels, and *Phragmites* distribution, density and growth performance.

Over 35 years of observations across the Lake Eyre supergroup case study of GAB springs suggest that small-scale fencing of individual springs provides limited conservation return for a relatively high cost. It is preferable from a conservation viewpoint to protect groups of springs. We therefore recommend prioritising protection of groups of springs that include a mosaic of springs with vegetation communities where *Phragmites* is present, and other springs where it is absent. Protecting this landscape mosaic may result in greater heterogeneity and vegetation diversity over time than protection of a group of springs which all contain *Phragmites*.

Acknowledgements

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Author Profiles

Simon Lewis is a retired South Australian public servant, having spent most of his 34-year career in the State Environment Department. He first travelled to the GAB springs in 1977 and, from the early 1980s, was involved in the spring fencing program which is the focus of the case study described in this paper. Simon led the annual spring vegetation monitoring program at these springs from the mid-1980s until 2005. He is a foundation member of Friends of Mound Springs and is the long-standing Secretary of that group.

Jasmin Packer has been fascinated by Great Artesian Basin springs since visiting several during her childhood. She is a Research Fellow at the Environment Institute, The University of Adelaide, and involved in international research collaborations on invasion science, including *Phragmites australis* as a global model species. Jasmin is passionate about protecting our threatened communities and species by bringing together world-class science with on-ground management. Jasmin and Friends of Mound Springs have been collaborating since 2017 to progress this shared vision.

Five Decades of Watching Mound Springs in South Australia

Colin Harris[1]

Abstract

Australia's mound springs, or artesian springs as they are more generically known, are natural outlets for the pressurised ground waters of the Great Artesian Basin (GAB) and occur in the far north of South Australia, north-western New South Wales, and western and south-western inland regions of Queensland. The springs in South Australia are aligned in a great arc around the southern and south-western margins of the GAB and are particularly well developed near Lake Eyre and at Dalhousie Springs north-east of Oodnadatta. It has been my good fortune to have been closely associated with the South Australian springs for five decades, both professionally and in a personal capacity, and in this paper I reflect on those five decades and what they might offer in terms of managing the springs more effectively into the future.

Keywords: Great Artesian Basin springs, South Australia, cultural and environmental importance, conservation initiatives, management issues, involvement of Indigenous people

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Introduction

I saw my first mound spring in 1971, but my interest had been piqued much earlier. In the mid-1950s I was in primary school and my attention had been drawn to an intriguing photograph in a South Australian Social Studies textbook. It was the impressive sand bubble of the Bubbler mound spring near Lake Eyre South, and the accompanying text described the mound springs as one of the wonders of the Australian Inland (Education Department SA, 1955). To an impressionable young boy the notion of freshwater springs in an otherwise harsh desert environment did indeed seem a wondrous thing.

I made a mental note to visit these oases in the desert, and when the opportunity came some fifteen or so years later, it was, felicitously enough, the Bubbler and nearby Blanche Cup Springs that I first visited. They were every bit as intriguing as the writer of that textbook had suggested, and a year later I was back, this time to the spectacular Dalhousie Springs on the western margins of the Simpson Desert (Figure 1). Shortly after, I was recruited to the newly established South Australian Environment Department where for thirty years mound springs and the GAB were an important part of my work program. In retirement I joined with a group of like-minded colleagues and friends to establish the community group Friends of Mound Springs (FOMS), and in spite of our advancing years we remain active in the conservation of springs in South Australia.

What all this amounts to is five decades of watching springs in northern South Australia. There have been many changes in that time, some for the better, some not, and the observations and thoughts that I have garnered may provide some pointers to how springs might be managed more effectively.

The Early Years, 1970s

At the time that I made my first visit to South Australia's springs country, there was quite a deal of public interest in the centenary of the Overland

Telegraph Line (OT), one of the most remarkable technological achievements of 19th-century colonial Australia (Taylor, 1980; Moyal, 1984). With its completion in 1872, Australia could communicate almost instantaneously with the rest of the Western World, a far cry from ship-borne communications which could take many months. Construction of the OT had been made possible by the inland explorations a decade or so earlier of John McDouall Stuart (Stuart, 1865), the route that Stuart took on his successful crossing of the continent in 1861–1862 becoming, with only minor deviations, the route of the OT. In turn, Stuart had succeeded in his crossing because of the great arc of mound springs to the south and west of Lake Eyre. Providing potable water in some of the harshest desert country in Australia, the springs were the stepping stones that led him into central and northern Australia, and ultimately to the Arafura Sea and back.

Pastoralists had followed hard on the heels of Stuart, his reports of unfailing waters being an irresistible attraction, and when the narrow-gauge railway line north to Oodnadatta began creeping its way inland a decade or so after the OT line, an important trade and communications corridor had been established along the line of the springs (Figure 2). It was a remarkable nexus between the natural and cultural: the springs had determined the line of Stuart's explorations, the pastoralists followed and located their head stations on the springs, the OT followed a decade later (with the Strangways and Peake Repeater Stations located on the springs), and in the 1880s and early 1890s the railway pushed northwards to service the pastoral industry (Harris, 2002). Importantly though, all of this was simply a European manifestation of what Indigenous people such as the Arabana and Lower Southern Arrernte had been doing for millennia. The line of springs was a key trade and communications route for them, continent-wide song lines followed their path, and individual springs were of both utilitarian and mythological importance (McBryde, 1987). While they were supremely utilitarian in providing unfailing sources of water in dry times, when it came to the mythological they were not simply way-points in dreaming travels, but key sites where significant events had happened (Hercus, 1980).

Figure 1. Great Artesian Basin, principal areas of spring activity. Modified from Habermehl (1980) and Ponder (1986).

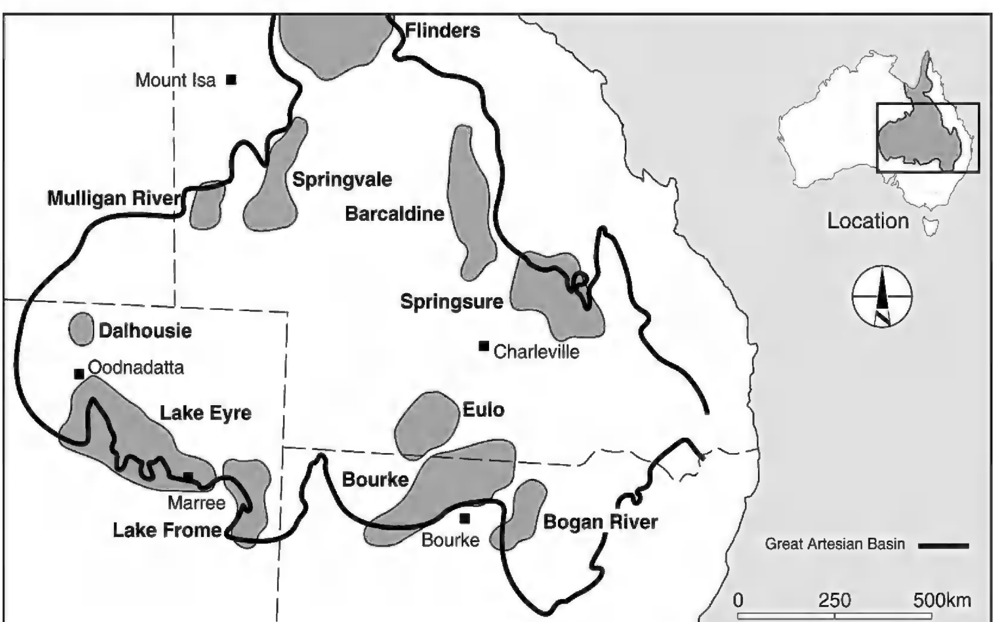
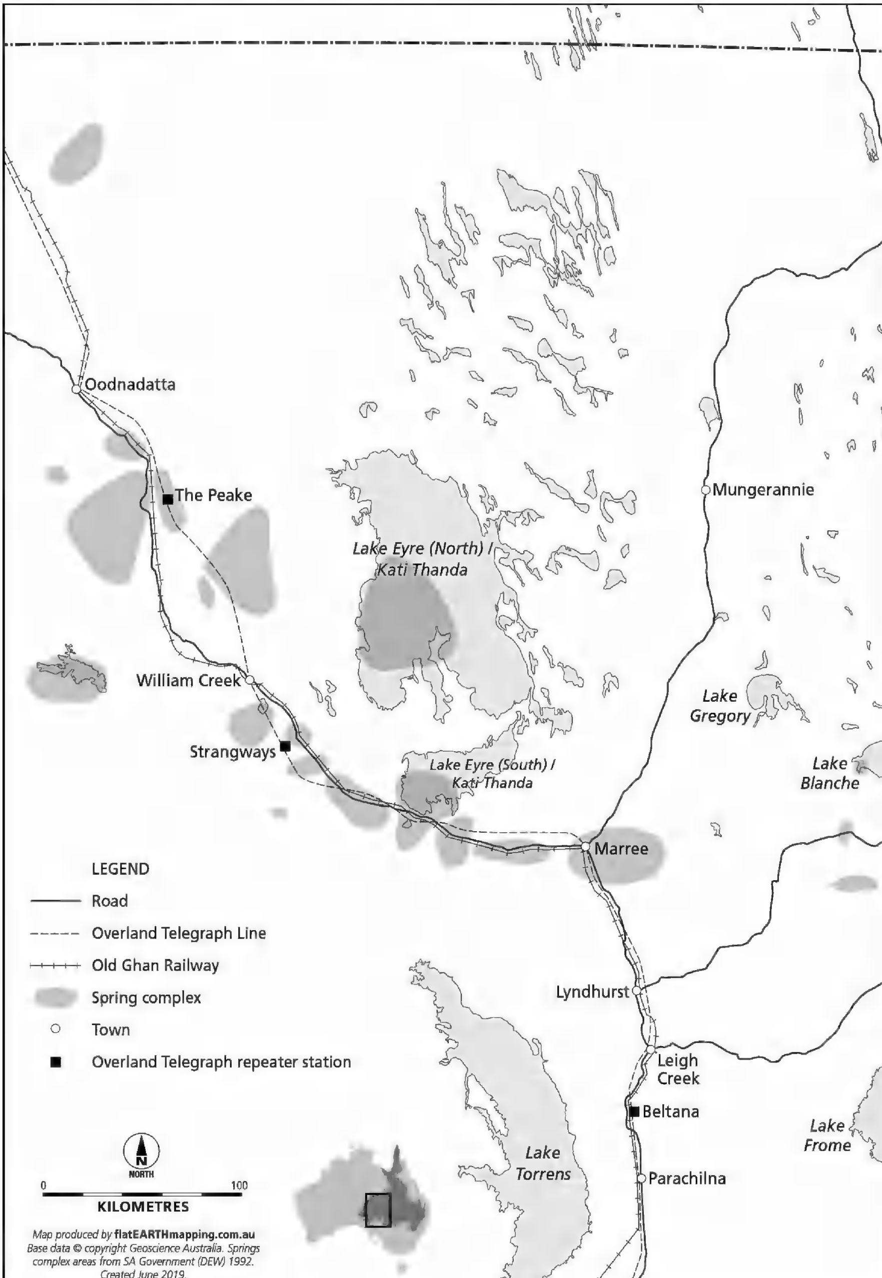


Figure 2. Mound springs and associated cultural features.



All of this had drawn me to the country in that initial visit of 1971, but other opportunities to visit soon followed. I was involved in post-graduate biogeography studies at the University of Adelaide at the time, and just over a year later (1972) I found myself at Dalhousie Springs with a group of scientists from Adelaide and the Australian National University (ANU) Canberra en route to the Simpson Desert. The Desert was the principal focus at the time, but the group of botanists, biologists and earth scientists put in several days around the sixty or so flowing springs. Some interesting findings emerged, particularly from the work of the late Dr Dick Barwick (ANU) who looked at ecological partitioning in the springs and the importance of thermoclines in the distribution of the (native) fish species. Regrettably, the latter work was not published; it would have been of importance in influencing a later decision of the South Australian Government to establish a major camping facility at the main spring. Swimming is allowed in the spring, and I have often wondered about the consequences of all that human activity in breaking down the previously well-defined thermoclines.

Early SA Government Work

A little over a year later (1973) I was part of the first intake of environmental officers to the newly established State Government Environment Department, and in one of those strange twists I was given a starting date that involved not reporting to the office, but instead rolling my swag and joining an interdepartmental party of State Government officials on a two-week inspection of the Marree-Oodnadatta country. Many of the key mound springs were included in the inspection, and professional and personal friendships developed from those first two weeks in the outback were to be of key importance in the later development of a conservation program for the springs.

One of the things that emerged from the inspection was that hydrogeologists in the South Australian Department of Mines already had a program under way to systematically record the location, flows and water chemistry of the springs. This work – continued over a period of some years in the 1970s – is now an important baseline inventory, poignant in some ways because it records flows from springs that are now, only a few decades on, extinct (Williams, 1974, 1979; Cobb, 1975). Tony Williams, who was involved in that work, also collaborated with John Holmes of Flinders University in a pioneering study that looked at using the areal extent of wetland vegetation as a surrogate for spring flow (Williams & Holmes, 1978). Interest in this methodology remains to the present, with satellite imagery being used to capture the ebb and flow of wetland areas around the springs. The Mines Department was also taking an interest in uncontrolled flowing bores, and in the late 1970s (well before the Great Artesian Basin Sustainability Initiative) it commenced a rehabilitation program (Boucat & Beal, 1977). To its credit, the Department recognised that a number of uncontrolled bores had been flowing for many years, creating wetlands of biodiversity interest. With this in mind it invited the State Environment Department to assess these wetlands before any rehabilitation was undertaken, and the outcome was agreement that at a number of bores a controlled flow would be maintained, albeit supporting smaller wetlands than those around the uncontrolled flows. Several decades on, the Great Artesian Basin Sustainability Initiative (GABSI) would provide a national framework and funding for bore rehabilitation work, and the recovery of local aquifer pressures was seen to be an important step in maintaining, and even recovering some spring flows.

Assessing the flowing bores also meant assessing a number of nearby or adjacent springs, a major perceived benefit of the bore rehabilitation being that a recovery of localised groundwater pressures would result in some recovery of spring flows, and in 1979 the State Environment Department released its first report on mound springs (Casperson, 1979). Even at that early stage the report documented high scientific and cultural values for the springs, foreshadowed further and more detailed studies, and raised the need for conservation measures such as stock-proof fencing at selected springs. I was a middle-level Manager in the Department by this time, and the mound springs work was being done under my direction. Perhaps unusually by Government conventions today, I was also active in a non-government organisation, the Nature Conservation Society of South Australia. The Society had a reputation for conducting sound biological surveys, and in view of the rising interest in springs it decided that the mound springs country between

Marree and Oodnadatta would be the survey region for 1978. In spite of the remoteness, the Society assembled a strong team, and over a ten-day period up to thirty biologists, earth scientists and field naturalists participated, supported by a dozen 4WD vehicles and two light aircraft. Amongst the highlights were the rediscovery of the salt pipewort, *Eriocaulon carsonii*, a plant endemic to the springs, and the collection of a new species of ostracod, *Ngarawa dirga* (Greenslade et al., 1985). It was an important contribution to our understanding of the springs, and although a compilation of the collected results did not appear for some time, much of the data was pressed into immediate use, both within and outside of government.

A Rapid Growth of Interest – Olympic Dam Mine

Even with this rising tide of interest, relatively few people knew of the springs, and it would be safe to say that even fewer were concerned about their conservation status. All of this was about to change, however, for by the late 1970s it had become clear that mineral exploration to the west of Lake Torrens, in a region known to geologists as the Stuart Shelf, had confirmed the presence of an ore body with world-ranking quantities of copper (fourth largest in the world), uranium (largest in the world), silver, gold (fourth largest in the world) and rare earth elements (Showers, 1999; Johns, 2010). Western Mining Corporation, the company that had made the discovery, subsequently entered into a joint venture arrangement (1979) with BP Australia to develop the prospect, and in the early 1980s the joint venture commissioned studies for a draft environmental impact statement.

From the outset, what had become known as the Olympic Dam Mine proposal attracted considerable interest and controversy. Whilst there was plenty of support for the predicted economic stimulus a mine at that scale would bring for South Australia, there was also plenty of opposition. The opposition focused on two main concerns: South Australia's prospective involvement in the nuclear cycle, which many people were passionately opposed to; and the proposed extraction of up to 32 megalitres (ML) of water a day from the GAB for process water at the mine and its treatment plants, and for the support town of Roxby Downs to be located near the mine. Whilst the proposed mine and its infrastructure were located around 100 kilometres from the southern margins of the GAB, the extraction of GAB water was to take place (initially) near Lake Eyre South, from where it would be pumped south (Kinhill-Stearns Roger, 1982). Borefield A, where the production bores would be located, had many mound springs in close proximity, and the localised drop in pressure that would result from the water extraction raised many legitimate concerns about impacts on the springs.

In spite of the opposition, including a regional presence of anti-uranium protesters for several years, environmental, social and economic studies were eventually concluded, the mine approved, and an opening site ceremony conducted on 5 November 1988. Mining continues to the present, although now under the ownership of BHP. Expansion plans are frequently mooted, and the projected life of the mine is widely accepted to be many decades. Around 42 ML of GAB water is now being used for the mining operation daily. This water is principally being extracted from Borefield B, which was established in the late 1990s to the east of Lake Eyre North, but with some extraction from the original Borefield A – all of which understates the high politics, the contention and the controversy that the project generated.

Although environmental impact assessment was not part of my departmental brief, I knew the springs well by that time and I became involved in much of the Olympic Dam environmental impact statement (EIS) work, particularly when it came to GAB extractions and the likely spring impacts. The backdrop to the work was the political intensity of the whole issue, and I was variously described by opposing camps at the time as a mouthpiece for the conservation movement and an apologist for industry. Offsetting all this high drama was the fact that in the course of it all I had the good fortune to become acquainted with some outstanding scientists, including Dr Rien Habermehl of the then Bureau of Mineral Resources Canberra, at that time Australia's pre-eminent GAB hydrogeologist; Dr Winston Ponder from the Australian Museum, an expert on freshwater tateids – of which there are many new and endemic genera and species in the springs; his colleague Dr Wolfgang Zeidler from the SA Museum; and the late Dr Luise Hercus,

a linguist from the ANU Canberra and an outstanding authority on the importance of the springs to Indigenous Australians. All have added a great deal to our understanding of the springs, and their contributions to the EIS work of the early to mid-1980s were highly important.

SA State Government Initiatives

At the same time that the EIS work was under way, the South Australian Environment Department was becoming much more actively involved in its own studies of the springs, paradoxically enough because of the perceived threat from the Olympic Dam mine proposal. It was more than a little ironical that it had taken an external threat to stimulate the flow of funds, but those of us committed to conservation of the springs were not too concerned about such things. We welcomed the investment and, with Commonwealth funding available to bolster State contributions, four important consultancy studies were commissioned and undertaken in 1984–1985: one dealt with the biological values of the springs, a second surveyed the archaeology of the springs, a third the cultural significance of the springs to Indigenous people, and the final report documented their non-Indigenous (principally, though not exclusively, European) heritage values (SADEP, 1986). The archaeological work, although necessarily brief, was the first of its kind to be undertaken in the region, and the non-Indigenous settlement history became a basis for the subsequent State Heritage listing of a number of significant sites and objects along the Oodnadatta Track.

The biological survey was always going to be challenging because of the areal extent of the springs and the difficulties of ground access to them in quite remote country. The survey became even more challenging when heavy rains closed many roads and tracks before work had even begun. Fortunately, however, the Commonwealth Government stepped in with additional funding to cover helicopter charter costs, and this proved to be a very rapid and effective way of reaching springs. Far more were sampled than would have been possible under the original plan to use ground access. The Indigenous cultural assessment was largely desktop, but extremely effective and important because it gathered together information that Luise Hercus had been recording from traditional Indigenous custodians, her many field trips to the region having begun in the late 1960s. It remains to the present the definitive work on the Indigenous cultural heritage of the springs (SADEP, 1986).

The South Australian Environment Department had two main reasons for commissioning these surveys: first, to place the Olympic Dam EIS work being done by the joint venture partners into a broader regional context; and second, to establish some priorities for springs to be fenced on pastoral lease country. In a Presidential address that I had delivered to the Royal Geographical Society of Australasia (SA Branch) Inc. in 1981, I had identified fencing of selected high-priority springs as the single most important conservation initiative needed at that time (Harris, 1981), and with completion of the surveys we set about obtaining funding for this, mostly Commonwealth, though with some private sector and non-government contributions. The statutory body responsible for pastoral country in South Australia, the Pastoral Board, then facilitated negotiations with the pastoral lessees involved, and by late 1988 ten springs had been fenced against cattle and feral donkeys and horses. The fencing was constructed to a high standard, and over thirty years later the exclosures remain intact (Figure 3). Partly because of funding constraints and partly because some lessees wanted continued access to water from the springs, the exclosures are small, ranging in size from 0.1 ha to 9.2 ha. Some biologists criticised the fencing initiative, arguing that a lesser number of exclosures, but with a greater number of spring vents and tails within each one, would have provided greater biodiversity (Fatchen, 2000). In the light of what we now know about springs biology and biogeography, that is true; but at the time it seemed a reasonable decision, especially as the choice of springs was also influenced by both Indigenous and non-Indigenous cultural heritage values. Our intent was to fence as many high-priority springs as possible.

We were also criticised because of the very rapid proliferation of *Phragmites australis*, and to a lesser extent *Typha domingensis* within the exclosures in the wake of the cessation of grazing. The concern was focused on the competitive effect of this on other plants associated with the springs and the loss of open pools of water known to provide habitat for a range of invertebrates, some endemic

to particular springs or spring complexes (Fatchen, 2000). In a 1992 paper reviewing the South Australian springs initiatives, I addressed this in part by posing the question of floristic dynamics in the pre-European grazing environment (Harris, 1992). Whilst megafauna such as the *Diprotodon* would have undoubtedly grazed the springs vegetation, that grazing ceased around 35,000–40,000 years ago and there are numerous references to dense *Phragmites* in early European accounts of the springs. The accompanying sketch of Louden Spa (north of present-day William Creek) dates from John McDouall Stuart's exploration, and the dense, high growth of *Phragmites* is particularly interesting in this context (Figure 4). It is also the case that after thirty years of protection from grazing, the *Phragmites* in some of the exclosures is beginning to senesce, presumably as the high stock-induced loadings of nutrients decline over time. A more detailed consideration of *Phragmites* and the springs is the subject of the paper by Lewis and Packer (2020).

Figure 3. Mound springs – conservation parks and fenced springs. Bolding indicates fenced springs.

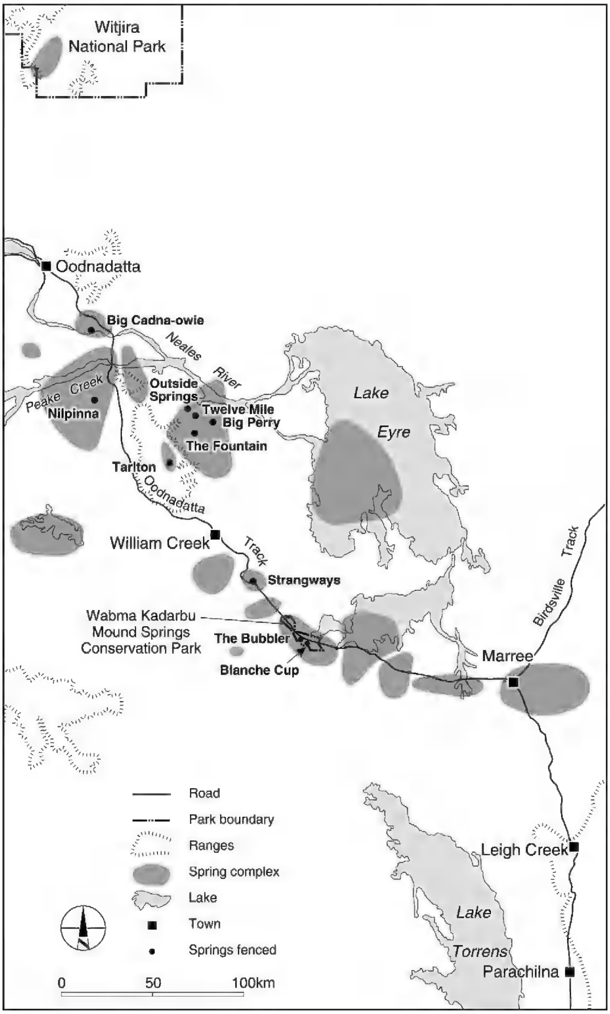


Figure 4. Louden Spa, showing high and dense *Phragmites* growth. *Source*: GF Angas, based on sketches from McDouall Stuart expeditions, 1859–1862 (Stuart, 1865). Some care is needed as Angas had not seen the country and there may be some artistic licence in his portrayal of the reed growth. This spring ceased to flow in the 1970s and is now extinct (Source: National Library of Australia, nla.pican22891603-v).

Establishment of Witjira and Wabma Kadarbu Parks

At the same time that the departmental surveys of the springs were being undertaken, Dr Winston Ponder and Dr Wolfgang Zeidler, two of the key scientists previously mentioned in the context of the Olympic Dam EIS, initiated an independent study of Dalhousie Springs. Funded by the invited participants, the survey was conducted in June 1985 and the results were published several years later (Zeidler & Ponder, 1989). Coincidentally, and prior to the Dalhousie survey, an opportunity had arisen to establish the first protected area under the *National Parks and Wildlife Act 1972*, specifically for springs conservation. The acquisition of Mt Dare station to protect Dalhousie Springs had been mooted as early as 1970, but at the time the lessee, Rex Lowe, was unwilling to sell and the Government of the day was not prepared to resume the lease. By the mid-1980s, however, that situation had changed and, with Lowe as a willing seller, negotiation and acquisition proceeded quickly, with the 7769 square kilometre Witjira National Park constituted in 1985 (Cohen, 1989) (Figure 3). While the establishment of the park removed cattle grazing from the springs, it also opened them to tourism. Lowe had actively discouraged visitors to the springs, but once in the public domain the situation changed dramatically, especially as 4WD Simpson Desert crossings increased in popularity. A formal campground at the main spring now functions as the most frequently used gateway to the Desert, its warm waters a widely publicised attraction. Although I had been actively involved within the Department in the acquisition of Witjira, I was opposed to the later development of the campground, believing that the endemic native fish and invertebrates were too important to be subject to such heavy visitor pressure, particularly in the light of the thermoclines and ecological partitioning mentioned earlier in this paper. It was an internal debate that I lost, but it remains my belief that camping should be away from the springs, with the main springs a day-visit site with no swimming.

A second park specifically for mound springs conservation was established a decade later near Lake Eyre South. Embracing the Blanche Cup and Bubbler Springs on the Oodnadatta Track – long regarded as classic mound springs because of their morphology and flow – it was constituted in 1996 and with a later extension is now the 12,016 ha Wabma Kadarbu Mound Springs Conservation Park. Unlike the situation at Dalhousie Springs, it is a day-visit park with no camping and swimming: camping facilities are provided at the nearby, privately operated Coward Springs Campground.

The completion of comprehensive springs surveys, the establishment of the two parks and the stock-proof fencing of a number of key springs represented some substantial progress, and in my 1992 paper I had reflected on improvements for the better in the decade following my 1981 review (albeit that Wabma Kadarbu Mound Springs Conservation Park had not been established at that stage). Within the Department our attention at this time was primarily focused on managing the two parks and monitoring the fenced exclosures as the springs vegetation responded to the relaxation of decades of livestock grazing pressure.

Through all of this over many years, we received a great deal of invaluable advice and support from the traditional owners of the land, the Arabana in the Marree-Oodnadatta country and the Southern Arrernte at Witjira. It was both a privilege and a pleasure for me to work with Arabana elders at sites along the Oodnadatta Track; and to become acquainted with senior custodians of Southern Arrernte traditions and law at Witjira. In 2007 the Witjira National Park Co-management Board was established, with the Irrwanyere Aboriginal Corporation as the management authority for the Park. In 2012 the Arabana Parks Advisory Committee was established, with the Arabana Aboriginal Corporation as an advisory body for park management, but likely to become a co-management board for Wabma Kadarbu and Kati Thanda-Lake Eyre parks at some stage in the future.

Interest in the springs amongst researchers, both in South Australia and interstate, remained high at this time, and in 1997 I was one of the organisers of an informal gathering of researchers from a variety of institutions who met in Adelaide to provide reports and updates on their springs work. The gathering was deemed to be of real value and was repeated multiple times over the next decade or so (Niejalke, 1998; Department for Environment, Heritage & Aboriginal Affairs, 2000; Halliday, 2001; Environment Australia, 2002; Gotch et al., 2006). The SA Environment Department facilitated most of the events, which we had initially dubbed Mound Springs Researchers Forum(s), although the topics and the attendees covered a range of Great Artesian Basin issues and interests. The seventh, and last, was held in Adelaide in March 2013, as part of the Great Artesian Basin Researchers Forum.

Community Involvement

After thirty years in the SA Environment Department and its various incarnations over that time, I retired in 2003. A close colleague in all things mound springs, Simon Lewis, retired three years later, and in 2006 we set about establishing a community group, Friends of Mound Springs (FOMS), one of many volunteer conservation groups in South Australia operating under the umbrella of a parent organisation, Friends of Parks Inc. A sister group, Friends of Simpson Desert Parks (FOS), had been established some years before and was providing voluntary assistance at Dalhousie Springs, and with this in mind FOMS made an early decision to focus its efforts on the springs between Marree and Oodnadatta, leaving FOS to continue its work with Dalhousie. FOMS has been an active group with a good blend of capabilities amongst its membership, and has picked up awards for both biological and heritage conservation work at the springs (https://www.friendsofmoundsprings.org.au/). At the same time – like many community groups – it has an ageing membership profile, and succession to a younger age cohort remains a challenge.

Coinciding with this has been a steady withdrawal of State Government involvement from mound springs conservation. Subject to ongoing budgetary constraints over many years, the State Environment Department has suffered major budget cuts in recent years. For the mound springs country, remote and expensive to access, this translates to a struggle to fulfil even basic statutory commitments to manage the two springs parks. Additionally, the Department has withdrawn almost entirely from maintenance and monitoring of the fenced exclosures protecting springs on pastoral lease country,

leaving the void to be filled by FOMS in a voluntary capacity. This is clearly not sustainable: the continuity of voluntary organisations into the future can never be guaranteed, and the maintenance of remote areas fencing from Adelaide, or even Port Augusta, makes no sense. When the exclosures were constructed over thirty years ago, it was envisaged that arrangements would be negotiated with the respective pastoral lessees for routine maintenance. For a variety of reasons this has not happened, and one of the failures of our approach to off-park conservation of springs has been an inability to actively engage and involve the lessees in the program.

Some Concluding Thoughts

Lest all this seem a rather gloomy note to conclude on, I need to say that we know very much more about mound springs now than when I first became interested in them, all those years ago. Local aquifer pressures have been helped by GABSI (and earlier South Australian Government bore rehabilitation work), a lot of very good biological, hydrogeological and cultural heritage work has been carried out over the decades, important parks have been established to conserve spring values, and livestock exclosures have been established and monitored for over three decades.

It has been my privilege to be involved in much of this work. However, under current governance and funding arrangements, I believe that within both State Government and the non-government organisations we have extended ourselves as far as we can. We will need to be innovative if we are to consolidate the gains of the past and do things better into the future. For this we will need new paradigms and models for good outcomes. Amongst other things, we will certainly need to involve regional stakeholders far more than has been the case hitherto, the pastoral lessees especially, as it is on their stations that most of the unprotected springs occur. And we will certainly need to use the knowledge and connections to the land of its traditional owners more effectively. The legal niceties of Native Title aside, Indigenous people hold moral title to the land, and it is incumbent that we all work together to conserve these remarkable features of our inland landscape.

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Colin Harris is a retired South Australian public servant who spent 30 years of his career in the State Environment Department. At the time of retirement he was Director of Biodiversity Conservation. He has been actively involved in the conservation and management of mound springs since the early 1970s and for this, and other conservation work, he was awarded the Public Service Medal in 1999. He is the foundation President of the Friends of Mound Springs and continues to the present in that role.

Current State and Reassessment of Threatened Species Status of Invertebrates Endemic to Great Artesian Basin Springs

Renee A. Rossini[1]

Abstract

Springs are unusual freshwater ecosystems of high cultural and conservation significance, yet they are often overlooked in discussions of global freshwater biodiversity, ecology and conservation. Springs that emerge from the Great Artesian Basin (GAB) in Australia support a high diversity of endemic aquatic species. The majority of these species are at high risk of extinction due to their small geographic ranges, severe habitat loss and ongoing threats. However, the ecological requirements of most spring biota are poorly understood and the majority are unprotected, particularly invertebrates, for which basic taxonomic and ecological information is lacking for numerous species. This assessment of threat status determined that 98% of molluscs and 80% of crustaceans endemic to GAB springs meet the criteria for designation of 'critically endangered' under the Australian *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (the EPBC Act). However, none of these species is currently listed. The analyses in this paper provide support for individual EPBC listing of all species of gastropods and crustaceans.

Keywords: springs, invertebrates, endemic species, threats to springs, conservation status, Great Artesian Basin

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Introduction

Freshwater environments are amongst the most altered and under-conserved global ecosystems, despite being 'hotspots' of cultural significance and endemic diversity (Geist, 2011; Strayer & Dudgeon, 2010). Freshwater environments that depend on groundwater, such as springs, are particularly vulnerable because increasing water demands are leading to significant anthropogenic alteration of the groundwater sources that sustain them (Cantonati et al., 2012; El-Saied et al., 2015; Fairfax & Fensham, 2002; Famiglietti, 2014; Kreamer & Springer, 2008; Nevill et al., 2010; Powell et al., 2015; Stevens & Meretsky, 2008; Unmack & Minckley, 2008). Despite the pertinent threats springs face, they are rarely included in global assessments of freshwater biodiversity, ecology or conservation (Cantonati et al., 2012). Springs are unique and diverse freshwater ecosystems that emerge in a range of landscapes, but those in arid regions are particularly important because they provide a reliable source of water in areas characterised by water scarcity and impermanence (Davis et al., 2013, 2017). They act as 'islands' of hospitable wetlands in a 'sea' of aridity (Ponder, 1995) that are used as watering points for broadly distributed species, as well as providing critical wetland environments for suites of organisms endemic to springs (Fensham et al., 2011; Myers & Resh, 1999). Extensive spring systems are present in the arid and semi-arid regions of most continents, with each region sharing parallel stories of unique features, fragility, threat and destruction (Powell & Fensham, 2016; Unmack & Minckley, 2008).

Arid zone springs fed by the Australian Great Artesian Basin (GAB) have been a focus of both Indigenous and colonial use because they provide a reliable source of water in prevailingly dry portions of the continent. The chain of GAB springs that

extends from Kati Thanda–Lake Eyre to north-east Queensland forms vital points in the lore and song-lines of numerous First Peoples (Harris, 2002; Potezny, 1989), and springs remain important sources of material and spiritual inspiration for traditional custodians (Ah Chee, 1995; Moggridge, 2020). Springs facilitated the occupancy and stocking of the arid interior during the early colonial period, and by 1895, water inspectors documented the use and alteration of many Queensland springs (Fairfax & Fensham, 2002; Powell et al., 2015). Physical alteration of springs and extraction of water from the GAB using bores drastically increased with agricultural intensification, leading to increased extraction volumes and decreased water pressure within the GAB. This caused a large proportion of springs to become dormant (Fairfax & Fensham, 2002; Powell et al., 2015). The loss of GAB springs is of concern because of their extremely high biological and cultural values, and because their demise is a sign of the broader issue of diminished pressure in the aquifer at large. Nation-wide schemes to regain GAB pressure by capping bores have been enacted (e.g. the GAB Sustainability Initiative (GABSI); Brake, 2020).

Discharge springs that survived the initial broad-scale habitat loss post-1890 remain exposed to a range of threatening processes (Davis et al., 2017). Continued extraction of water from the GAB creates further pressure loss, leading to the extinction of springs and populations of endemic species that occupy them (Mudd, 2000), or the permanent alteration of spring chemistry (Shand et al., 2013). Industries with high water demands (e.g. mining and intensive agriculture) magnify this threat, and models of how these threats will affect springs and their biodiversity provide limited predictions at best (Mudd, 2000). Springs that survive drawdown remain exposed to introduced species. Introduced plants and nutrient-led changes to the dynamics of native species mean that some species grow to dominate springs (e.g. Holmquist et al., 2011) and can diminish the spring pools vital to the persistence of aquatic animals (Kodric-Brown & Brown, 2007; Lewis & Packer, 2020). Ungulates trample springs, with pigs being particularly destructive as they actively uproot vegetation (Kovac & Mackay, 2009). Invasive aquatic fauna living within the springs (including invertebrates, amphibians and fish) consume or compete with species endemic to springs, in some cases to the point of near extinction (Kerezsy & Fensham, 2013). Although the excessive drawdown associated with unchecked water extraction from the GAB has been ameliorated by programs such as GABSI, risky extraction licenses are still being granted (Currell, 2016; Currell et al., 2017) and these additional threatening processes continue to affect the unique biodiversity that exists in GAB springs.

Relative few of the species currently described as endemic to GAB springs have been the subject of detailed published accounts regarding their distribution, population numbers and ecology. For those species for which detailed population and distribution data are available, it appears common for species to be restricted to a single spring complex, or numerous complexes in the same locality (Fensham et al., 2011). Populations of species endemic to the GAB spring wetlands are rarely found in all springs within an occupied complex, and the particular springs occupied tend to change through time (Fensham & Fairfax 2002; Kerezsy & Fensham, 2013; Ponder et al., 1989; Worthington-Wilmer et al., 2008). Extirpations in a single spring seem relatively common over decadal time scales, but species can persist within their broader geographic range due to the presence of an ever-shifting set of viable populations (Worthington-Wilmer et al., 2011). These patterns of spring occupancy appear to vary across species, with different species occupying different sets of springs and displaying different patterns of population connectivity (Murphy et al., 2010). Consequently, some springs are more diverse (Kodric-Brown & Brown, 1993; Ponder et al., 1989) or maintain populations over longer periods, whilst others host only one particular species for a short time (Worthington-Wilmer et al., 2011). As small geographic range appears to be the norm, it is probable that severe biodiversity losses accompanied the broad-scale loss of springs that occurred post-1890 (Fensham et al., 2010). Habitat loss that has not led to extinction is still associated with the loss of genetic diversity (Faulks et al., 2017) and the potential loss of cryptic species or clades before they are discovered or described (Mudd, 2000).

Despite the unique nature of GAB springs, and the severity of the threats they face, these wetlands have only recently attracted state and

Commonwealth conservation attention, although they were cared for previously under customary systems (Moggridge, 2020). The flora and fauna associated with springs came under Commonwealth protection in 2001, via a blanket listing of "the community of native species dependent on natural discharge of groundwater from the GAB" as 'endangered' under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act, 1999). The effectiveness of this legislation is contingent on a range of factors, but of relevance is the need for up-to-date and accurate information regarding patterns of endemic diversity, distribution and threat (Pointon & Rossini, 2020). However, appraisals of the species that compose the endangered community, their distribution, and the information available about them, generally remain focused on particular broad taxonomic groups, such as plants (Fensham & Price, 2004; Silccock, 2017) and snails (Ponder, 1995), or are locality-specific, e.g. Edgbaston Springs (Ponder et al., 2010). The extensive review that accompanied the original Recovery Plan (Fensham et al., 2010) remained the only system-wide analysis until the publication of a review of the biogeographical patterns of endemic biodiversity in GAB springs (Rossini et al., 2018), with both assessments excluding whole classes of taxa due to data deficiency.

In some cases, species identified as being at particularly high risk of extinction are afforded additional protection through individual EPBC listing (e.g. the red-finned blue-eye, *Scaturiginichthys vermeilipinnis*; Wager & Unmack, 2004). This listing has resulted in far more intensive conservation attention and effort for the red-finned blue eye and is likely the reason it has dodged extinction to date. Whether all species that require this level of additional protection should or can be listed is an important consideration. Some invertebrates with small geographic ranges that have experienced significant population declines are classified as 'critically endangered' under the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species (IUCN, 2001). However, the effort required to review and submit an application to list the hundreds of species endemic to GAB springs is a major barrier to equivalent assessment of all taxa. Despite this barrier, it is surprising that none of the species listed by the IUCN is listed individually as threatened species under EPBC legislation.

Lack of attention to invertebrates that are at risk of extinction in springs is representative of a global trend that hinders conservation efforts in freshwater systems (Bland et al., 2012; Cardoso et al., 2011; Strayer, 2006). In Australia, populations of some of the most restricted and threatened invertebrate taxa remain un-monitored and un-managed on private grazing properties. For example, resurveying in 2020 of the freshwater snail *Jardinella colmani* (Ponder, 1996) revealed all populations being directly exposed to grazing, very few springs with the species remaining, and severe disturbance to >80% of the springs sampled (Rossini, unpublished data). Data concerning the patterns of distribution and abundance of invertebrate species, and ongoing monitoring programs concerning species within the threatened community in general, are rare. Existing monitoring programs often employ different sampling methodologies that may render data inaccurate due to methodological biases (Cantonati et al., 2007; Cheal et al., 1993; Rosati et al., 2016). Current conservation practices generally focus on local scales, and rest heavily on stock exclusion and attempts to eradicate invasive flora and fauna (Kodric-Brown & Brown, 2007; Lewis & Packer, 2020; Peck, 2020). In systems where long-term monitoring is occurring, such interventions can be evaluated; however, a lack of published baseline data for most spring complexes means the effectiveness of management practices is rarely assessed quantitatively (for exceptions, see Kerezsy & Fensham, 2013; Kovac & Mackay, 2009; Peck, 2020). Calls are being made for managed relocation and captive breeding programs to protect species from extinction (Lawler & Olden, 2011), and levels of 'acceptable' drawdown of spring waters are being set (Lewis et al., 2018). However, the potential success of these initiatives is constrained by a lack of data regarding the true diversity, population numbers, patterns of occupancy, and the environmental requirements of most endemic invertebrate species (Ponder & Walker, 2003).

In an attempt to collate the information that is available, and translate it into an up-to-date assessment of the threatened species status of invertebrates endemic to the GAB springs system, this paper aims to:

1. Present a case study of fundamental challenges associated with the estimation of metrics that are essential to assessments of conservation status under EPBC criteria. These are the geographic range (EoO – extent of occurrence) and the habitable or inhabited area (AoO – area of occupancy) for each species. The case study uses data on gastropods endemic to the Pelican Creek Springs complex to illustrate issues around accurate estimation of EoO and AoO peculiar to springs.
2. Summarise the availability of data needed to assess threat status for all known invertebrate species, or evolutionarily significant units, in GAB springs (using data listed in Rossini et al., 2018).
3. Assess the current conservation status of invertebrate taxa from the same list under IUCN and EPBC criteria.

Methods

Case Study: Endemic Gastropods of the Pelican Creek Springs

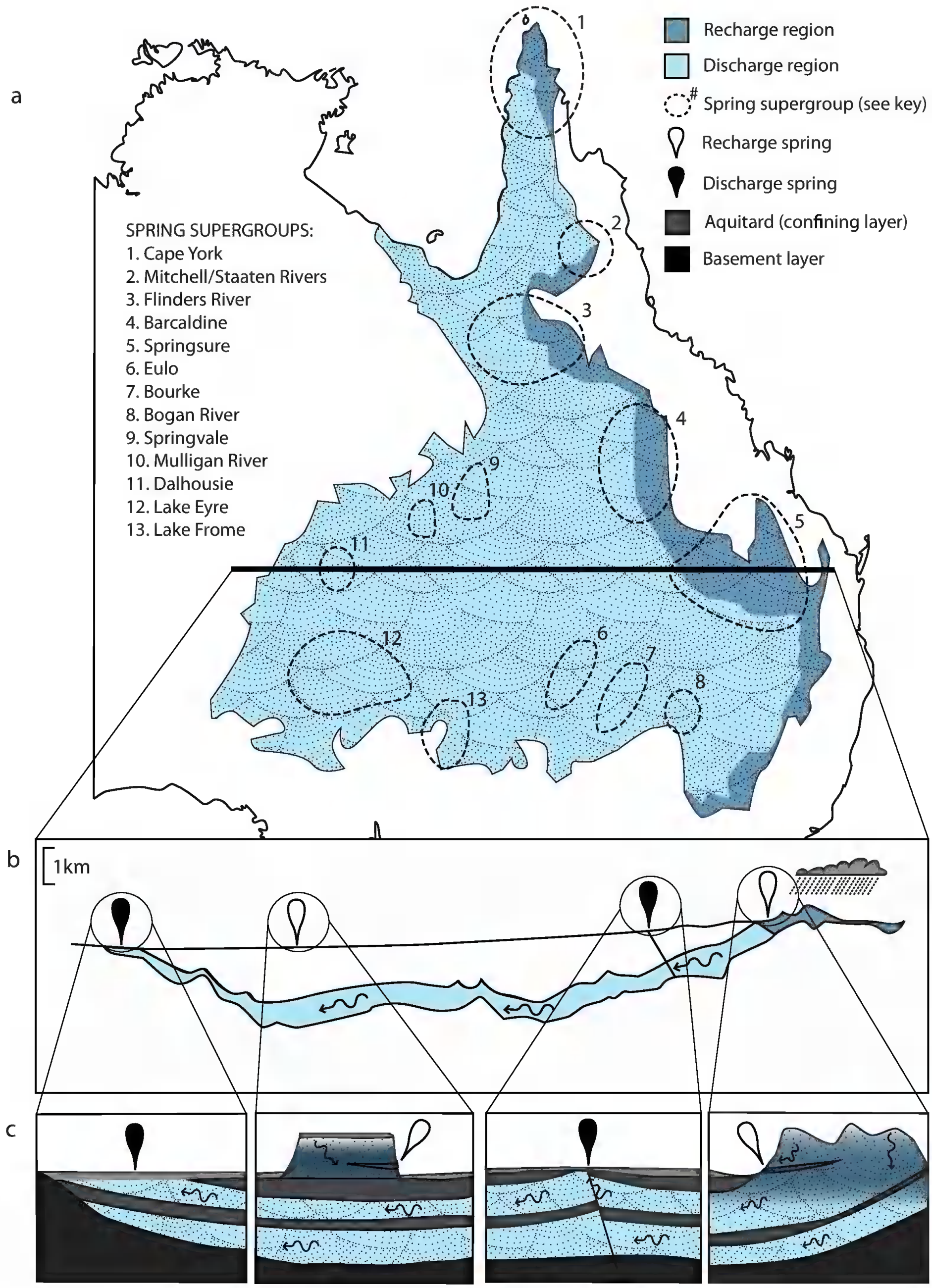
The northern portion of the Pelican Creek Springs complex is enclosed within the Edgbaston Reserve (managed by Bush Heritage Australia), within the Barcaldine supergroup located in central Queensland (Figure 1). Springs of the Pelican Creek complex are spread across a north-to-south axis, with the northern springs at the base of a rocky escarpment (latitude –22.725° to –22.721°), the central springs mostly within a large clay pan and scald (latitude –22.725° to –22.74°) and the southern springs within, or in the proximity of, a large ephemeral waterbody, Lake Mueller (which drains into the nearby Aramac Creek) (latitude –22.74° to –22.76°). The complex continues to the south of Lake Mueller, into an adjoining property outside of Edgbaston Reserve that contains additional endemic species. These springs all have shallow open-water pools of a limnocrenic morphology (Springer & Stevens, 2008). The Pelican Creek Springs complex, as a whole, comprises ~145 springs, with 113 of those within the Edgbaston Reserve. This complex was chosen for the case study as within-complex distribution studies have been conducted for most invertebrate species, and ecological information regarding within-spring restrictions on distribution are available for most endemic gastropod species.

Assessments of wetland area, species distributions and summations for assessments of the threatened species status of endemic gastropod species at the Pelican Creek complex were conducted in 2015 as part of the annual invertebrate surveys of the Bush Heritage Australia portion of the complex.

Spring wetland area was estimated as a rhombus of the maximum length and width (a polygon) of the vegetated area of each spring. Size of distribution was calculated at three scales: spring supergroup; across springs of the Pelican Creek complex; and within springs of the Pelican Creek complex. At the supergroup scale, frequency of occurrence (how many complexes are occupied, FoO) and extent of occurrence (the area within a polygon around the springs, EoO) and the total potential area of occupancy (AoO) were measured as the total wetland area within the supergroup.

Springs species operate as meta-populations, and in theory individuals are free to move about the complex and occupy a subset of springs at any one time. However, empirical data suggest that considering all springs to be occupied by any particular species at any one time is likely to generate an overestimate of AoO. Therefore, at a within-complex scale, the number of springs occupied by each species as a total and percentage of all springs in the complex, and the minimum limit of environmental variables of significance, were calculated to determine the accuracy of the AoO as a measure of the true inhabited area for each species. At a within-spring scale, species were allocated to a distribution category (P = pool only; T = tail only; P(T) = higher abundance in pool but also occupies tail) using data from the literature (Rossini et al., 2017a). The pool areas of GAB springs at the Edgbaston complex have consistently different environmental conditions (Rossini et al., 2017a) and represent a subset of the total spring area. Therefore, estimating the area of wetland available to a pool-restricted species (the AoO) using the total spring area will significantly overestimate their available useable habitat. For any species with sufficient evidence to suggest it is restricted to spring pool areas, area of occupied wetland (AoO) was calculated using the total pool area of all occupied springs in the Pelican complex instead of the total spring area.

Figure 1. Conceptualisation of the Great Artesian Basin showing: (a) the location of spring supergroups, location of aquifer discharge and recharge zones; (b) & (c) hydrogeological cross-section depicting water sources and flow paths to discharge and recharge springs.



Meta-analysis of Data Availability and Threat

The taxa list used for this part of the study is that presented in a review by Rossini et al. (2018). Logic used for differentiating spring complexes, defining endemic taxa and surveying the literature can be found in this publication. The state of data deficiency regarding each taxon included in the 2018 review was assessed. The amount of published information regarding each taxon was categorised (Table 1) in each of the key areas of data deficiency identified as hindering the conservation of invertebrates (Cardoso et al., 2011); these include taxonomy, distribution, abundance, ecology and threat, as well as patterns of population connectivity or divergence as recommended by Murphy et al. (2015a, 2015b). For each taxon, the amount of information available from the peer-reviewed literature was scored on an ordinal scale using the criteria detailed in Table 1 and added to give a final score. Whilst interactions between data deficiencies are likely (e.g. it is difficult to understand the impact of a threatening process without ecological or distribution data), this analysis applied an additive model for simplicity. Using this system, a taxon for which data that could be considered sufficient to make an assessment of conservation status scores high (maximum score of 24), whereas a taxon for which minimal information is available regarding any of these categories of data scores low (minimum score 4).

Table 1. The parameters used to score literature information on data availability for each endemic taxon included in this review of conservation status.

Data category	Score	Conditions
Taxonomy	4	Full morphological description supported by genetic assessment of relationship to other taxa and the potential of cryptic species complex if it occupies >1 complex or supergroup.
	3	In-depth morphological description with brief genetic analysis at species level; if range >1 complex, no in-depth enquiry into cryptic species.
	2	Morphological description but no genetic data.
	1	Remains undescribed.
Distribution	4	Full survey of range, regular (>1) and/or ongoing temporally replicated surveys of patch occupancy in at least one part of the range.
	3	Rudimentary knowledge regarding patch occupancy within the range from 1 or few disparate surveys, with no regular temporal element.
	2	No data regarding full range as yet; no ongoing monitoring.
	1	Few specimens from one or few visits.
Abundance	4	Temporally replicated (>1 time) systematically collected abundance assessments across >5 springs within the range.
	3	Robust anecdotal observations regarding relative abundance within most springs in the range.
	2	One-off or limited anecdotal observations within some parts of the range.
	1	No information.
Connectivity	4	Patch level data regarding population connectivity across at least 50% of the range.
	3	Spatially limited but detailed patch level data for part of the range (e.g. one group of springs within one complex).
	2	Anecdotal observations regarding potential connectivity in the system or patterns inferred from data in other similar species.
	1	No information.

Data category	Score	Conditions
Ecology	4	Extensive spatially and temporally replicated information regarding environmental correlates of occupancy and abundance, seasonal variance, trophic ecology, reproductive ecology, physiological limits or behaviour.
	3	Robust but not systematic observations regarding microhabitat associations, environmental limits, and responses to environmental variance from part of the range.
	2	Anecdotal observations regarding potential associations with some element of the environment (e.g. only in pools; found in billabongs and springs) or physiological limits.
	1	No information.
Threat	4	Experimental and/or temporally replicated observations regarding species' response to possible threats.
	3	Robust knowledge regarding some threats but not the full range or their potential to interact.
	2	Anecdotal and/or expert opinion regarding the potential response to threats but no explicit testing.
	1	No information.

Threat assessments were conducted using the criteria given by both the IUCN Red List and the EPBC Threatened Species assessment (IUCN, 2001; TSSC, 2018). The core criteria are listed as column headings in Table 2 below, and details of the criteria needed to meet each category of threat are available in each assessment guide, respectively. Species extent of occurrence (EoO) was calculated using a minimum bounding polygon in Google Earth Pro^{TM} (Version 7.3.2). The author has incorporated additional caveats specific to springs regarding the number of springs occupied (EoO) or the number of springs offering suitable habitat within a springs complex (AoO). These caveats were incorporated to account for spring complexes where the polygon containing all springs is large but the available habitat (i.e. number and area of springs likely to be inhabited) is small. The importance of this caveat is explored in the case study presented above for endemic gastropods in Pelican Creek Springs.

Estimating evidence of decline was critical for differentiating species threat levels. The Lake Eyre Basin Springs Assessment (LEBSA) database was used to assess, for each species, what portion of its range has disappeared (South Australian springs data reported in DEWNR, 2015; Queensland springs data held by the Queensland Herbarium). Unfortunately, this estimate only considers habitat decline at a spring complex scale and cannot incorporate habitat loss within the complex (i.e. reduction of the area of individual spring wetlands) or extirpations caused by severe disturbance to individual springs.

The proportion of the complex experiencing habitat quality reduction due to invasive species or pollutants was inferred from the LEBSA database (disturbance) and from the GAB springs risk assessment conducted by Kennard et al. (2018). Threats from groundwater drawdown were attributed using the calculated threats given in Kennard et al. (2018). Threatened species distributions and taxa vulnerability scores were also derived from this source. The percentage of springs with damage was extracted from the LEBSA database.

Results

Case Study: Endemic Gastropods of the Pelican Creek Springs

Nine species were included in this analysis: *Gyraulus (Gy.) edgbastonensis* (Brown, 2001), an undescribed species of *Glyptophysa* sp. considered to be endemic to the Pelican Creek Springs complex (Ponder et al., 2016), *Gabbia (Ga.) fontana* (Ponder, 2003), *Jardinella acuminata*, *J. corrugata*, *J. edgbastonensis*, *J. jesswiseae*, *J. pallida* and *Edgbastonia alanwillsi* (Ponder et al., 2008; Ponder & Clark, 1990).

These species have a small global distribution warranting listing as critically endangered under the IUCN criteria. The extent of occurrence (EoO) of any species endemic to the Pelican Creek complex is 29.7 km^2 and all species are considered to have the same EoO. However, within that 29.7 km^2, the area of occupancy (AoO) – the inhabited or theoretically habitable amount of spring wetland – is only 0.3% (~0.028 km^2). No species at this complex occupies all springs or all areas within them. At most, the eight species occupy 36% of springs, and at the least one species occupies only 6% (Table 2). Therefore, in the most extreme case the EoO overestimates the actual occupied wetland area by >99%, as a species that occupies only a few springs and is restricted to only the pool areas of those springs has an AoO of ~3212 m^2 of wetland (e.g. *Glyptophysa* sp., Table 2).

Basin-wide Analysis: Data Availability

Across all taxa, there are differences in how much information is currently available to inform an assessment of extinction risk (Figure 2). For 30% of taxa, a formal taxonomic description is yet to be published. Good to extensive data are available regarding the presence or absence of taxa among spring complexes, but knowledge concerning taxon distributions at finer spatial scales (i.e. among individual springs within complexes) is available for only ~70% of taxa. For >75% of organisms there are no published estimates of abundance anywhere within their range, nor information concerning the connectivity between populations. There is no literature at all regarding the basic ecology of >50% of taxa, and for the vast majority of species there is little quantitative information regarding how they respond to threatening processes (Figure 2).

The relative quantity and nature of the available data differ considerably across taxonomic groups. Of all groups, the fishes have the highest scores (Figure 3), but some taxa still score low (e.g. the Dalhousie catfish, *Neosiluris gloveri*). The molluscs have the broadest range of data availability scores (Figure 3), with equal numbers scoring the highest (e.g. *Fonscochlea* and *Trochidrobia*) and the lowest (e.g. *Glyptophysa* and *Gabbia*) (Figure 3). The low-scoring taxa tend to be within the less diverse families (e.g. the only species of bivalve scored lowest). Both groups of crustaceans considered here scored moderately (Figure 3), and low-scoring taxa are from radiations outside of the Kati Thanda system (i.e. both species of *Ponderiella* and an undescribed *Austrochiltonia* from Queensland). Most plant taxa fall within the moderate range of scores, although three species have low scores for data availability (*Isotoma*, *Chloris* and *Peplidium*) (Figure 3).

Basin-wide Analysis: Threatened Species Status of Endemic Invertebrates

The current level of listing under the IUCN and EPBC criteria does not reflect the present assessed threat status of invertebrate species endemic to discharge springs of the GAB (Figure 4). At the time of publication, no invertebrate taxa were listed individually as a threatened species under EPBC legislation, whereas 14 taxa have been assessed under the IUCN criteria, all of them molluscs. The assessment presented here recommends that 20 endemic species should be listed under the IUCN as critically endangered (5 crustaceans, 15 molluscs), 19 be listed as endangered (4 crustaceans, 15 molluscs) and 15 be listed as vulnerable (6 crustaceans, 9 molluscs). When assessed using the EPBC criteria, 50 species are recommended for critically endangered listing. This is an extreme estimate, so a revised EPBC listing has also been presented based on the relative threats currently faced by each species.

Figure 2. The varying levels of data deficiency for different information types (taxonomy, distribution, abundance, connectivity, ecology, threats) identified across all taxa (red = data deficient; orange = basic data; yellow = good data; and green = extensive data) (Source: Renee Rossini).

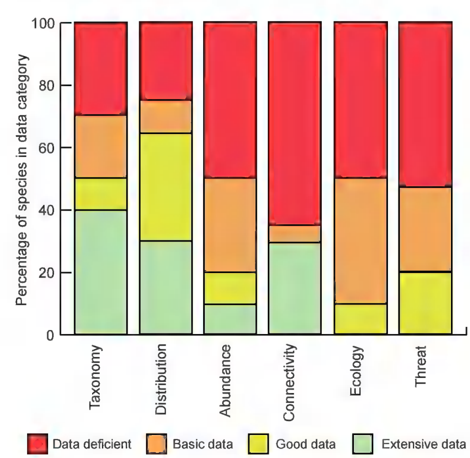


Table 2. Summary of estimates of distribution under different calculation methods for six species of GAB spring gastropod endemic to the Pelican Creek Springs complex. Calculations at a supergroup scale include frequency of occurrence (FoO) representing how many complexes the species occupies; extent of occurrence (EoO) is the area of a minimum bounding polygon around all springs in the complex; and area of occupancy (AoO) is the total available wetland area within the EoO. Considering detailed distribution data for each species at a spring complex scale allows refined estimates of AoO (occupiable spring wetland) to be calculated. With the addition of within-spring distribution data, these estimates can be refined further to reflect the true wetland area occupied by the species (corrected AoO).

	Supergroup scale			Complex scale Environmental limits					Within-spring scale Environmental limits				
	FoO	**EoO (km^2)**	**AoO (km^2)**	**No. of springs (% total)**	**Spring size (m^2)**	**Pool size (m^2) Pool depth (cm)**	**Area of wetland that meets limits (km^2)**	**Area of wetland occupied**	**Conductivity (μS)**	**pH**	**Depth (mm)**	**Habitat Category**	**Corrected AoO (km^2) (as % of AoO)**
Tateidae													
Jardinella acuminata	1	29.7	0.09	11 (13%)	>1000	>5 m^2 >5 cm	0.07	0.04	<1500	<8.5	>8	P	0.004 (4%)
Jardinella jesswiseae	1	29.7	0.09	25 (29%)	>100	>0 m^2 >1 cm	0.08	0.04	<1500	<8.5	>8	P(T)	0.07 (78%)
Jardinella edgbastonensis	1	29.7	0.09	31 (36%)	>1	>0 m^2 ≥0 cm	0.09	0.05	<1500	<9.0	>1	T	0.05 (56%)
Planorbidae													
Glytophysa sp.	1	29.7	0.09	5 (6%)	>1000	>10 m^2 >5 cm	0.05	0.03	<1500	<8.5	>10	P	0.003 (4%)
Gyraulus edgbastonensis	1	29.7	0.09	10 (13%)	>100	>5 m^2 >5 cm	0.08	0.03	<1500	<8.5	>10	P	0.003 (4%)
Bythiniidae													
Gabbia fontana	1	29.7	0.09	12 (13%)	>100	>5 m^2 >5 cm	0.05	0.03	<2000	<9.0	>5	P(T)	0.03 (33%)

Figure 3. Total data availability score out of 20 (4 points for each of 5 data categories) for each species identified in Rossini et al. (2018) as being endemic to discharge springs fed by waters of the Great Artesian Basin (Source: Renee Rossini).

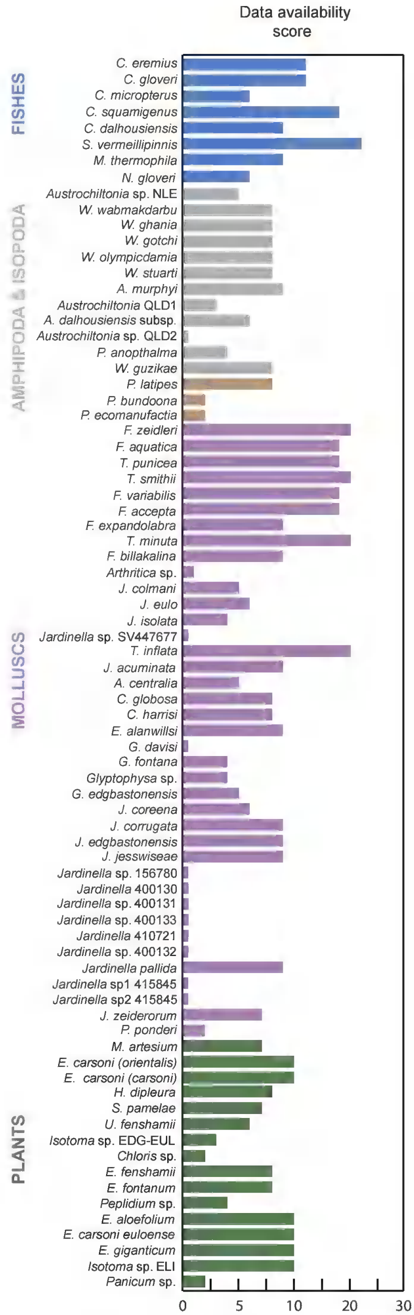
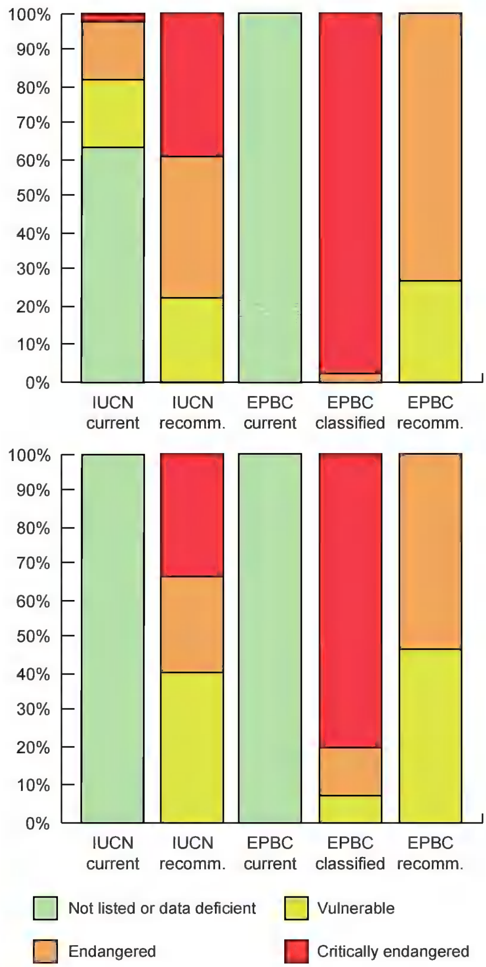


Figure 4. Summary of current listings, classified listings and recommended listings for molluscs (top) and crustaceans (bottom) endemic to discharge springs of the Great Artesian Basin. Taxa not yet described at species level have been excluded here but are classified in Appendix 1.



All taxa are at the critically endangered level for the extent of occurrence (EoO) criteria, which demonstrates how the further restriction placed by the EPBC assessment framework for two or more additional elements can be applied logically in cases where the spring wetland system creates naturally small distributions and the habitat is innately fragmented. In addition, by qualifying the risks associated with restricted ranges by the number of supergroups occupied and the number of springs available, some differentiation emerges between species. More than 50% of taxa satisfy the 'severely low number of locations' criteria, and 29 species have <50 springs available within their overall distribution (83% with <20 springs). If both of these elements are considered necessary to satisfy the low number of locations criteria, taxa from a single complex with very few springs are likely to have a higher level of extinction risk (primarily those from small complexes in the basins to the north of the GAB) than those widely distributed over multiple complexes in the basins to the south (Figure 1).

Exposure to threatening processes is generally ubiquitous across taxa and helps to differentiate those with narrow distributions and more pertinent threats from those that may be relatively stable. Drawdown as a process has affected some areas of the basin more than others. Across species that have seen drawdown within their range, few have experienced above-average losses. Unfortunately, complexes where the strongest losses of springs due to drawdown have been recorded are likely to have seen extinction of fauna before a full census had been completed (e.g. Flinders River supergroup, all supergroups in New South Wales). Most taxa are exposed to introduced alien species for which there is ample evidence that they can be considered vulnerable. For example, snail species endemic to Edgbaston Springs have been found in high frequency in the stomachs of both the cane toad, *Rhinella marina* (Clifford et al., 2020) and the alien fish, *Gambusia holbrooki* (Unmack, pers. comms). Populations of *G. holbrooki* often far exceed those of endemic fishes. For example, estimates of *G. holbrooki* populations in a subset of springs at the Edgbaston Springs complex in 2016 suggested that up to 30,000 individuals are present in a single spring (Alexander Burton, unpublished data), whilst naturally occurring *S. vermeillipinnis* populations average 2000 individuals (Fairfax et al., 2007). This hyperabundance of predators undoubtedly influences invertebrate prey populations; however, no time-series data are currently available to test the effect of *G. holbrooki* colonisation and proliferation on populations of endemic invertebrates.

Most species have part or all of their distribution outside of conservation areas, where they

are exposed to uninhibited ungulate disturbance (Table 3). There is very little published information on the effects of ungulate disturbance on threatened invertebrate persistence (for exceptions, see Kovac & Mackay, 2009; Peck, 2020). There is reason to believe pugging by pigs and cows and rooting by pigs will have a detrimental effect on endemic invertebrates. The initial disturbance event can be severe, uprooting plants, mixing sediments, elevating salinity and increasing eutrophication through defecation and decay. In mound-forming springs, ungulate disturbance can expose or damage travertine deposits, changing spring mound shape. Many invertebrate taxa included in this assessment are bacterial film feeders or sediment grazers (e.g. crustaceans, Choy, 2020; gastropods, Ponder, 1995). These films attach to sediment grains or the surfaces of plants and presumably require clear water and time to establish. Post-disturbance recovery will most likely disrupt these food resources. The gastropods at least require hard surfaces to attach egg capsules, again disrupted by physical disturbance. The physical change in bathymetry caused by vertebrate pugging changes flow patterns, where water once flowing continuously over the wetland area forms numerous small, isolated pools within pugged sediments. Due to the low flow of many springs, they can take years to return to the pre-disturbance state (e.g. one spring at Edgbaston disturbed in mid-2000 is still noticeably pugged over a decade later; Peck, pers. obs, 2020).

Discussion and Recommendations

In recent years, threats to groundwater systems (Famiglietti, 2014) and the diverse array of species that rely on them (Boulton, 2005; Danielopol et al., 2003) have been highlighted as issues of global concern. The GAB is a unique groundwater system that, at present, has largely avoided the broad-scale disturbance and loss that has occurred in other extensive aquifer systems in other arid landscapes (El-Saied et al., 2015; Famiglietti, 2014; Powell & Fensham, 2016). Nevertheless, acknowledgement of severe declines in discharge and loss of spring wetlands over the past 200 years (Fairfax & Fensham, 2002), and the pertinent threats that remained in the system, culminated in 2001 with the protection of species reliant on GAB springs as an endangered community (Fensham et al., 2010). However, this blanket listing of the GAB spring community is not necessarily sufficiently robust to protect endemic spring species from further declines (Pointon & Rossini, 2020), and the present analysis suggests there is justification for listing most endemic spring invertebrates as threatened species in their own right.

Based on the available evidence, >50% of endemic GAB spring taxa should be listed as threatened species under both the IUCN and EPBC criteria. These taxa are spread across the basin with species ascribed critically endangered status under the standard EPBC criteria occurring in all major spring supergroups that contain endemic species. The nature of springs as an environment is to be spatially clustered and provide small patches of specialised habitat – i.e. they are inherently fragmented and restricted to small areas of wetland habitat. Due to these characteristics, all species assessed herein satisfy the critically endangered criteria for limited spatial distribution under the EPBC Act. Whilst retaining the standard EPBC method of threat status aligns GAB spring species with assessments of threatened species outside of springs, it does not accurately capture the different risks for endemic taxa within GAB spring wetlands. By further quantifying the 'small geographic distribution' criteria to include spring-specific criteria (e.g. number of springs within the complex, pool vs. tail habitat), the present assessment under the EPBC Act more accurately reflects the different levels of risk for spring invertebrates, and potentially taxa other than invertebrates. Under this revised EPBC listing, it is not suggested that any species should be listed as critically endangered; however, this assessment is highly conservative and is primarily an effort to align these suggested listings with the only existing listings within the GAB for fauna. At present the only species listed as critically endangered under IUCN criteria is the red-finned blue-eye (*Scaturiginichthys vermeilipinnis*) and the snail *Jardinella colmani*. Under EPBC Act criteria, the highest level of listing is endangered and only applied to *Scaturiginichthys vermeilipinnis*. The IUCN conservation status of fishes has been revised herein (Kerezsy, 2020) and the listing of plants was revised recently (Silcock et al., 2015; Silcock & Fensham, 2019). An accurate assessment of risk of extinction will need to involve a discussion of

all lifeforms, and ensure the same methods and criteria are applied to all taxa. The present assessment is a first step towards that end. However, some hurdles remain for accurately assessing extinction risk of GAB springs taxa, especially invertebrates and other under-researched groups.

First, data availability and present understanding of extinction risk strongly interact. The way to estimate spatial distribution, and the information available concerning the habitat associations of each species, affect perceptions of susceptibility to extinction. As demonstrated in the case study from Pelican Creek Springs, without information on the number of springs in a complex, their total wetland area and pool area, the total number of springs occupied and the environmental limits of each species, we cannot accurately estimate the area of occupancy (AoO) and must rely on a severe overestimate of EoO (i.e. the total spring wetland area within the complex). In lieu of accurate spring wetland extent and limitations of ecological information, this assessment has attempted to qualify the EoO and differentiate species based on whether 'all their eggs are in one basket' at two spatial scales. At the supergroup scale this has involved scoring the number of locations supporting each species; this criterion is important because species endemic to a single spring complex are more at risk than those occupying numerous complexes. Within the occupied complexes, scores are based on the total number of springs potentially available to inhabit. These are still likely to be overestimates of spatial restriction, given no species in the Pelican springs case study occupied more than 30% of springs in the complex. Collecting the data needed to remedy this data deficiency is relatively simple (Rossini et al., 2016), rapid, and robust to the use of different methods if estimates of presence/absence are all that is required. However, it is time consuming and costly to survey each species' distribution in detail, and finding the resources needed to access remote GAB sites is difficult. In other taxa, prioritisations like the Red List have helped focus survey efforts. A systematic and strategic program to target surveys towards filling knowledge gaps which prioritise species at greatest risk would greatly improve understanding of threat and extinction risks to GAB springs taxa.

No analyses of cryptic species complexes or population structure have been completed for species outside of Kati Thanda–Lake Eyre. Given that most species subjected to such enquiries have been split into species or subspecies complexes, calculations of available spring habitat for species as they are currently defined could be overestimates. For example, when the amphipod lineages endemic to Kati Thanda were considered as a single species (as they were prior to Murphy et al., 2009) their EoO encompassed the majority of Kati Thanda and was >1000 km^2, which is beyond the limits of a species whose distribution is considered as vulnerable to extinction according to the IUCN criteria. However, after identification of cryptic species, all are ranked as critically endangered (Table 4). To work within this limitation, all classifications have been conducted for each species and for each clade or subunit based on evidence from the literature. Listing currently undescribed cryptic species, or clades of a single species, can be difficult (Pointon & Rossini, 2020) but worthwhile; including such information in the threatened community listing will help to quantify the level at which a loss of a spring population will significantly impact genetic diversity within the species. Clarity regarding both the extent of available habitat for these organisms and accurate estimates of species richness and genetic structure are vital for accurately assessing a species' extinction risk (Ponder et al., 1995), as is information on quantifiable limits of 'significant impacts' that jeopardise persistence (Pointon & Rossini, 2020).

For species where information is available, such as the gastropods from the Pelican Creek Springs, understanding the extreme limits on their distributions helps to clarify and conceptualise their susceptibility to threatening processes. Basin-wide threats such as artesian drawdown caused the loss of up to 50% of springs within some endemic species distributions (e.g. the undescribed member of the Tateidae – *Jardinella* AMS C.156780), and 24% of taxa have lost >10% of springs within their distribution range. These losses continue as drawdown causes the dormancy of springs. When a species has a global distribution of 10 shallow ponds with a total area smaller than an AFL football oval (e.g. *Gyraulus edgbastonensis*), the loss of a single spring is significant. As springs become reduced in area, any localised threats (e.g. trampling by cattle) will have more and more concentrated effects. With such a limited distribution comes an exacerbated risk;

the incursion of a small herd of cattle for a week, or the concentrated efforts of a few pigs in a single spring, can represent a disturbance to >20% of a species' global distribution. Furthermore, threats to springs are likely to interact synergistically (Côté et al., 2016); for example, in all species of gastropod tested from Pelican Creek, environmental extremes caused mortalities sooner in warmer months and in populations already persisting under elevated salinity or pH (Rossini et al., 2017a). Assessing these conservation risks via conceptualisations of threats and their interactions is the first step. Connecting the conceptualisations with a quantifiable understanding of how they affect populations is important for predicting population trends and designing management interventions. This can be done relatively easily (Ponder et al., 1989; Rossini et al., 2017b). For threats pertinent to much of the GAB (e.g. draw-down and ungulate disturbance) or for taxa whose range is severely limited, targeted quantifiable ecological assessments of how threat exposure influences population levels or dynamics would improve understanding of the potential for extinction.

The second obstacle to overcome in GAB springs conservation concerns scale. The GAB is one of the world's largest active groundwater systems, and GAB-dependant springs exist in remote or pastoral contexts. Knowledge and management are currently focused on particular complexes, but management is generally lacking in isolated spring complexes. By way of example, within the Barcaldine supergroup, the Pelican Creek complex has full distribution lists, relatively sound ecological information for target organisms (primarily fishes and snails) that include time-series needed to document decline, and threat-reducing interventions. This is thanks to extensive collaborative data collection since the 1990s. All other complexes within the Barcaldine supergroup are little known or studied, despite the fact that they also provide habitat for known endemic species, one of which is the only species of invertebrate endemic to the springs listed as critically endangered under IUCN criteria (*J. colmani*). Likewise, the Kati Thanda springs have been the focus of numerous dedicated taxonomic and ecological studies, but the nearby Lake Frome supergroup is lesser known and likely contains endemic species yet to be described. Given the sheer number of species and vastness of the area to be covered, basin-wide initiatives that guide a strategic approach to spring surveys, management interventions and conservation works will aid in avoiding species loss outside of well-known complexes (see Brake, 2020). Such prioritisation and planning create nothing but 'fantasy documents' if they are not supported financially (Cox, 2018). As most springs exist on private property, it is also essential for any such efforts to engage with and support relevant stakeholders. Conservation covenants, landholder support and education were all suggested in the Recovery Plan of 2010 and should be fostered in any basin-wide initiatives (Fensham et al., 2010).

The third and overarching conclusion of this paper is that invertebrate taxa are, according to current knowledge, the most diverse component of the threatened community of native species, but they are the most vulnerable. This statement stands until the biodiversity and threat within other crustacean groups, microinvertebrates and algae are better known. The invertebrates included in this assessment generally have narrow distributions, and strong dispersal and environmental limitations combine for many species to restrict them to tiny areas of habitat. They represent a diverse range of unique evolutionary narratives documenting the quaternary changes in the Australian continent. They present numerous examples of theory in action by epitomising the evolutionary consequences of restrictions on gene flow and environmental factors driving diversification as a process (Gotch et al., 2008; Murphy et al., 2015; Ponder, 1995). Yet invertebrates are the least represented in threatened species legislation, and evidently have the highest data deficiency of all taxa in the GAB system. Even though many are exposed to the same threatening processes as more charismatic fauna such as fishes, no species of endemic GAB invertebrate has been assessed or listed under the EPBC legislation. In many systems including springs (Hershler et al., 2014; Ponder & Walker, 2003), rates of extinction in the molluscs are highlighted as particularly concerning (Kay, 1995). This is a global problem for conservation (Cardoso et al., 2011), and particularly for freshwater systems where endemic invertebrates with restricted distributions make up most of the assemblage (Strayer, 2006). We owe it to *kwatye* (Arranda name for groundwater) species to do better, and hope this is a first step towards doing so.

Appendix 1

A reassessment of all invertebrate taxa under the criteria provided by the Environmental Protection and Biodiversity Conservation (EPBC) Act in Australia for the listing of threatened species. Recommended listing levels under the EPBC Act are provided, as well as under the IUCN Red List (as the categories in this assessment framework are similar). In many cases, the level of threatened species listing recommended using the assessment is different from that which is recommended. Recommended listings are based on current patterns of listing within the EPBC Act (i.e. highly threatened taxa such as the red-finned blue-eye are still only listed as Endangered).

	1. It has undergone, is suspected to have undergone, or is likely to undergo in the immediate future:				**2. Its geographic distribution is precarious.**									
	Reduction in area of occupancy or extent of occurrence		**Reduction in quality of habitat due to effects of introduced taxa or pollutants**		**Small geographic distribution**	**Plus 2 or 3 of:**								
	Extinction of springs at the designated % as evidence of decline in area of occupancy	Human modification to springs at the given % (if it is in multiple complexes, the % of complexes that score over 0.5)	Introduced aquatic flora or fauna present in X% of species range AND focal species deemed 'vulnerable' to them	% of complex in which threat exposure for 'animal disturbance' at occupied complex is >0.5 AND is outside of conservation management	Extent of occurrence measured as the area within the minimum bounding polygon is X	Severely low number of locations	AND/OR very few springs available	Scored more than 0.3 for groundwater drawn down (i.e. above average) in more than 50% of occupied complexes	Introduced taxa present in species range and focal species deemed 'vulnerable' to them	Anywhere where animal disturbance scored more than 0.5 in >50% of occurrences are outside of conservation = Y	Current IUCN listing	Rec. IUCN	Classified EPBC	Rec. EPBC
	CE >80	CE >80	CE >80	CE >80	CE <100 km^2	CE 1	CE <10							
	E >70	E >70	E >70	E >70	E <5000 km^2	E <=5	E <20							
	V >50	V >50	V >50	V >50	V <20,000 km^2	V <=10	V <50							
Arabunnachiltonia murphyi	–	–	–	CE	CE	E	–	Y	–	Y	NE	E (A1c, B1, B2bc)	E	V
Arthritica sp. AMS C.449156	–	V	–	CE	CE	E	–	Y	Y	Y	NE	E (A1ce, B1, B2bc)	CE	E
Austrochiltonia dalhousiensis sub.sp. *dalhousiensis*	–	–	V	–	CE	CE	–	Y	Y	–	NE	V (B1, B2b, D2)	CE	V
Austrochiltonia n.sp. (North Eyre)	–	–	–	CE	CE	V	–	–	–	Y	NE	V (B1, B2b, D2)	V	V
Austrochiltonia n.sp. AMSP68165	–	V	V	V	CE	E	–	–	Y	Y	NE	E (A1ce, B1, B2bc)	E	V
Austrochiltonia sp. AMS P68160	–	–	CE	CE	CE	CE	E	–	Y	Y	NE	CE (A1ce, B1, B2bc)	CE	E
Austropyrgus centralia	–	–	V	–	CE	CE	–	Y	Y	–	LC	V (B1, B2b, D2)	CE	V
Caldicochlea globosa	–	–	V	–	CE	CE	–	Y	Y	–	LC	V (B1, B2b, D2)	CE	V
Caldicochlea harrisi	–	–	V	–	CE	CE	–	Y	Y	–	LC	V (B1, B2b, D2)	CE	V
Edgbastonia allanwilsi	–	–	CE	CE	CE	CE	–	–	Y	Y	NE	EN (A1ce, B1abc)	CE	E
Fonscochlea accepta	–	–	–	CE	CE	–	–	Y	–	Y	V	V (D2)	CE	V
Fonscochlea aquatica	–	–	–	V	CE	–	–	Y	–	Y	EN	EN (B2ab)	CE	V

	1. It has undergone, is suspected to have undergone, or is likely to undergo in the immediate future:				2. Its geographic distribution is precarious.									
	Reduction in area of occupancy or extent of occurrence		Reduction in quality of habitat due to effects of introduced taxa or pollutants		Small geographic distribution	Plus 2 or 3 of:								
	Extinction of springs at the designated % as evidence of decline in area of occupancy	Human modification to springs at the given % (if it is in multiple complexes, the % of complexes that score over 0.5)	Introduced aquatic flora or fauna present in X% of species range AND focal species deemed 'vulnerable' to them	% of complex in which threat exposure for 'animal disturbance' at occupied complex is >0.5 AND is outside of conservation management	Extent of occurrence measured as the area within the minimum bounding polygon is X	Severely low number of locations	AND/OR very few springs available	Scored more than 0.3 for groundwater drawn down (i.e. above average) in more than 50% of occupied complexes	Introduced taxa present in species range and focal species deemed 'vulnerable' to them	Anywhere where animal disturbance scored more than 0.5 in >50% of occurrences are outside of conservation = Y	Current IUCN listing	Rec. IUCN	Classified EPBC	Rec. EPBC
	CE >80	CE >80	CE >80	CE >80	CE <100 km^2	CE 1	CE <10							
	E >70	E >70	E >70	E >70	E <5000 km^2	E <=5	E <20							
	V >50	V >50	V >50	V >50	V <20,000 km^2	V <=10	V <50							
Fonscochlea aquatica Clade A	—	—	CE	CE	CE	E	—	Y	Y	Y	NE	—	CE	E
Fonscochlea aquatica Clade B	—	—	—	CE	CE	V	—	Y	—	Y	NE	—	CE	V
Fonscochlea aquatica Clade C	—	—	—	CE	CE	E	—	Y	Y	Y	NE	—	CE	E
Fonscochlea aquatica Clade D	—	—	—	—	CE	—	—	—	—	—	NE	—	CE	—
Fonscochlea billakalina	—	—	—	CE	CE	E	—	Y	—	Y	EN	EN (A1ce, B1abc)	CE	E
Fonscochlea expandolabra	—	—	V	CE	CE	V	—	Y	Y	Y	NE	V (A1ce, B1, B2abc)	CE	V
Fonscochlea expandolabra Clade A	—	—	CE	CE	CE	E	—	Y	Y	Y	NE	—	CE	E
Fonscochlea expandolabra Clade B	—	—	—	CE	CE	V	—	Y	Y	Y	NE	—	CE	V
Fonscochlea variabilis	—	—	—	—	CE	—	—	—	Y	Y	NE	V (D2)	CE	—
Fonscochlea variabilis Clade A	—	—	—	—	CE	CE	E	—	—	—	NE	—	—	—
Fonscochlea variabilis Clade B	—	—	—	—	CE	—	—	—	—	—	NE	—	—	—
Fonscochlea zeidleri	—	—	—	V	CE	—	—	Y	Y	Y	NT	EN (B2ab)	CE	V
Fonscochlea zeidleri form A Clade A	V	—	—	CE	CE	CE	—	Y	Y	Y	NE	—	CE	E
Fonscochlea zeidleri form B Clade B	—	—	—	CE	CE	V	—	Y	—	Y	NE	—	CE	V
Fonscochlea zeidleri form A Clade C	—	—	—	CE	CE	—	—	Y	Y	Y	NE	—	CE	E
Fonscochlea zeidleri form A Clade D	—	—	—	—	CE	—	—	—	Y	—	NE	—	—	—
Fonscochlea zeidleri form A Clade E	—	—	—	CE	CE	V	—	Y	—	Y	NE	—	CE	V
Gabbia davisi	—	—	CE	CE	CE	CE	CE	—	Y	Y	NE	CE (A1ce, B1, B2bc)	CE	E
Gabbia fontana	—	—	CE	—	CE	CE	CE	—	Y	—	NE	EN (A1ce, B1abc)	CE	E
Glyptophysa n.sp.	—	—	CE	—	CE	CE	CE	—	Y	—	NE	EN (A1ce, B1abc)	CE	E
Gyraulus edgbastonensis	—	—	CE	—	CE	CE	CE	—	Y	—	DD	EN (A1ce, B1abc)	CE	E

	1. It has undergone, is suspected to have undergone, or is likely to undergo in the immediate future:				2. Its geographic distribution is precarious.									
	Reduction in area of occupancy or extent of occurrence		Reduction in quality of habitat due to effects of introduced taxa or pollutants		Small geographic distribution	Plus 2 or 3 of:								
	Extinction of springs at the designated % as evidence of decline in area of occupancy	Human modification to springs at the given % (if it is in multiple complexes, the % of complexes that score over 0.5)	Introduced aquatic flora or fauna present in X% of species range AND focal species deemed 'vulnerable' to them	% of complex in which threat exposure for 'animal disturbance' at occupied complex is >0.5 AND is outside of conservation management	Extent of occurrence measured as the area within the minimum bounding polygon is X	Severely low number of locations	AND/OR very few springs available	Scored more than 0.3 for groundwater drawn down (i.e. above average) in more than 50% of occupied complexes	Introduced taxa present in species range and focal species deemed 'vulnerable' to them	Anywhere where animal disturbance scored more than 0.5 in >50% of occurrences are outside of conservation = Y	Current IUCN listing	Rec. IUCN	Classified EPBC	Rec. EPBC
	CE >80	CE >80	CE >80	CE >80	CE <100 km^2	CE 1	CE <10							
	E >70	E >70	E >70	E >70	E <5000 km^2	E <=5	E <20							
	V >50	V >50	V >50	V >50	V <20,000 km^2	V <=10	V <50							
Jardinella acuminata	–	–	CE	–	CE	CE	CE	–	Y	–	E	EN (A1ce, B1abc)	CE	E
Jardinella colmani	–	–	CE	CE	CE	E	V	–	Y	Y	CE	CE (A1ce, B1, B2bc)	CE	E
Jardinella coreena	–	–	CE	CE	CE	CE	V	–	Y	Y	NE	CE (A1ce, B1, B2bc)	CE	E
Jardinella corrugata	–	–	CE	–	CE	CE	CE	–	Y	–	V	EN (A1ce, B1abc)	CE	E
Jardinella edgbastonensis	–	–	CE	–	CE	CE	–	–	Y	–	V	EN (A1ce, B1abc)	CE	E
Jardinella eulo	–	–	–	CE	CE	E	CE	–	–	Y	V	CE (A1ce, B1, B2bc)	CE	E
Jardinella isolata	–	–	–	–	CE	CE	–	Y	–	–	V	EN (A1ce, B1abc)	CE	E
Jardinella jesswiseae	–	–	CE	–	CE	CE	–	–	Y	–	E	EN (A1ce, B1abc)	CE	E
Jardinella n.sp. AMS C.156780 (sp1)	V	CE	CE	–	CE	CE	CE	–	Y	–	NE	CE (A1ce, B1, B2bc)	CE	E
Jardinella n.sp. AMS C.400130/ QMS05 (sp2)	–	–	–	CE	CE	CE	CE	–	–	Y	NE	CE (A1ce, B1, B2bc)	CE	E
Jardinella n.sp. AMS C.400131/ QMS04 uncoil (sp3)	–	–	CE	CE	CE	CE	E	–	Y	Y	NE	CE (A1ce, B1, B2bc)	CE	E
Jardinella n.sp. AMS C.400133/ QMS04 (sp4)	–	–	CE	CE	CE	CE	E	–	Y	Y	NE	CE (A1ce, B1, B2bc)	CE	E
Jardinella n.sp. AMS C.410721 (sp5)	–	–	CE	CE	CE	CE	E	–	Y	Y	NE	CE (A1ce, B1, B2bc)	CE	E
Jardinella n.sp. AMS C.400132/ QMS04 keel (sp6)	–	–	CE	CE	CE	CE	E	–	Y	Y	NE	CE (A1ce, B1, B2bc)	CE	E
Jardinella pallida	–	–	CE	–	CE	CE	CE	–	Y	–	E	EN (A1ce, B1abc)	CE	E

	1. It has undergone, is suspected to have undergone, or is likely to undergo in the immediate future:				2. Its geographic distribution is precarious.									
	Reduction in area of occupancy or extent of occurrence		Reduction in quality of habitat due to effects of introduced taxa or pollutants		Small geographic distribution	Plus 2 or 3 of:								
	Extinction of springs at the designated % as evidence of decline in area of occupancy	Human modification to springs at the given % (if it is in multiple complexes, the % of complexes that score over 0.5)	Introduced aquatic flora or fauna present in X% of species range AND focal species deemed 'vulnerable' to them	% of complex in which threat exposure for 'animal disturbance' at occupied complex is >0.5 AND is outside of conservation management	Extent of occurrence measured as the area within the minimum bounding polygon is X	Severely low number of locations	AND/OR very few springs available	Scored more than 0.3 for groundwater drawn down (i.e. above average) in more than 50% of occupied complexes	Introduced taxa present in species range and focal species deemed 'vulnerable' to them	Anywhere where animal disturbance scored more than 0.5 in >50% of occurrences are outside of conservation = Y	Current IUCN listing	Rec. IUCN	Classified EPBC	Rec. EPBC
	CE >80	CE >80	CE >80	CE >80	CE <100 km^2	CE 1	CE <10							
	E >70	E >70	E >70	E >70	E <5000 km^2	E <=5	E <20							
	V >50	V >50	V >50	V >50	V <20,000 km^2	V <=10	V <50							
Jardinella sp. AMS C.415845 (Myross) (sp1)	–	–	CE	CE	CE	CE	V	–	Y	Y	NE	CE (A1ce, B1, B2bc)	CE	E
Jardinella sp. AMS C.415845 (Myross) (sp2)	–	–	CE	CE	CE	CE	V	–	Y	Y	NE	CE (A1ce, B1, B2bc)	CE	E
Jardinella sp. AMS C.447677	–	–	–	CE	CE	E	E	–	–	Y	NE	CE (A1ce, B1, B2bc)	CE	E
Jardinella zeiderorum	–	–	CE	CE	CE	CE	V	–	Y	Y	NE	CE (A1ce, B1, B2bc)	CE	E
Phraetochiltonia anopthalma	–	–	V	–	CE	CE	–	Y	Y	–	LC	V (A1ce, B1, B2abc)	CE	V
Phraetomerus latipes	–	–	–	CE	CE	–	–	Y	–	Y	NE	EN (A1ce, B1abc)	CE	E
Phraetomerus latipes Clade C1	–	–	–	–	CE	–	–	–	–	–	NE	–	–	–
Phraetomerus latipes Clade C2	–	–	–	CE	CE	CE	–	Y	–	Y	NE	–	CE	E
Phraetomerus latipes Clade C3	–	–	CE	CE	CE	E	–	Y	Y	Y	NE	–	CE	V
Phraetomerus latipes Clade C4	–	–	–	CE	CE	CE	–	Y	–	Y	NE	–	CE	E
Phraetomerus latipes Clade S5	–	–	–	CE	CE	E	–	Y	Y	Y	NE	–	CE	E
Phraetomerus latipes Clade S6	–	–	–	CE	CE	V	–	Y	–	Y	NE	–	CE	V
Phraetomerus latipes Clade N7	–	–	V	CE	CE	E	E	Y	Y	Y	NE	–	CE	E
Phraetomerus latipes Clade N8	–	–	–	CE	CE	E	E	Y	–	Y	NE	–	CE	E
Phraetomerus latipes Clade N9	–	–	–	CE	CE	E	–	Y	–	Y	NE	–	CE	V
Ponderiella bundoona	–	V	CE	V	CE	E	E	Y	Y	Y	NE	CE (A1ce, B1, B2bc)	CE	E
Ponderiella ecomanufactia	–	V	CE	V	CE	E	E	Y	Y	Y	NE	CE (A1ce, B1, B2bc)	CE	E
Posticobia ponderi	–	–	–	–	CE	CE	CE	Y	–	–	NE	CE (A1ce, B1, B2bc)	CE	E

	1. It has undergone, is suspected to have undergone, or is likely to undergo in the immediate future:				**2. Its geographic distribution is precarious.**									
	Reduction in area of occupancy or extent of occurrence		**Reduction in quality of habitat due to effects of introduced taxa or pollutants**		**Small geographic distribution**	**Plus 2 or 3 of:**								
	Extinction of springs at the designated % as evidence of decline in area of occupancy	Human modification to springs at the given % (if it is in multiple complexes, the % of complexes that score over 0.5)	Introduced aquatic flora or fauna present in X% of species range AND focal species deemed 'vulnerable' to them	% of complex in which threat exposure for 'animal disturbance' at occupied complex is >0.5 AND is outside of conservation management	Extent of occurrence measured as the area within the minimum bounding polygon is X	Severely low number of locations	AND/OR very few springs available	Scored more than 0.3 for groundwater drawn down (i.e. above average) in more than 50% of occupied complexes	Introduced taxa present in species range and focal species deemed 'vulnerable' to them	Anywhere where animal disturbance scored more than 0.5 in >50% of occurrences are outside of conservation = Y	Current IUCN listing	Rec. IUCN	Classified EPBC	Rec. EPBC
	CE >80	CE >80	CE >80	CE >80	CE <100 km^2	CE 1	CE <10							
	E >70	E >70	E >70	E >70	E <5000 km^2	E <=5	E <20							
	V >50	V >50	V >50	V >50	V <20,000 km^2	V <=10	V <50							
Trochidrobia inflata	–	–	CE	CE	CE	E	–	Y	Y	Y	E	EN (A1ce, B1abc)	CE	E
Trochidrobia minuta	–	–	V	CE	CE	V	–	Y	Y	Y	V	V (A1ce, B1, B2abc)	CE	V
Trochidrobia punicea	–	–	–	–	CE	–	–	Y	–	Y	LC	V (A1ce, B1, B2abc)	CE	V
Trochidrobia punicea Clade A	–	–	–	–	CE	V	–	–	Y	–	NE	–	CE	–
Trochidrobia punicea Clade B	–	–	–	CE	CE	V	–	Y	–	Y	NE	–	CE	V
Trochidrobia smithii	–	–	–	E	CE	–	–	Y	–	Y	VU	V (A1ce, B1, B2abc)	CE	V
Trochidrobia smithii Clade A	–	–	–	CE	CE	V	–	Y	–	Y	NE	–	CE	V
Trochidrobia smithii Clade B	–	–	–	CE	CE	V	–	Y	–	Y	NE	–	CE	V
Trochidrobia smithii Clade C	–	–	–	–	CE	E	–	–	–	–	NE	–	–	–
Wangiannachiltonia ghania	–	–	–	CE	CE	E	–	Y	–	Y	NE	EN (A1ce, B1abc)	CE	E
Wangiannachiltonia gotchi	V	–	–	CE	CE	E	–	Y	–	Y	NE	CE (A1ce, B1, B2bc)	CE	E
Wangiannachiltonia guzikae	–	–	CE	CE	CE	CE	–	Y	Y	Y	NE	CE (A1ce, B1, B2bc)	CE	E
Wangiannachiltonia olympicdamia	–	–	–	CE	CE	E	–	Y	–	Y	NE	V (A1ce, B1, B2abc)	CE	V
Wangiannachiltonia stuarti	–	–	–	–	CE	E	–	–	–	–	NE	V (D2)	–	–
Wangiannachiltonia wabmakdarbu	–	–	–	–	CE	V	V	–	–	–	NE	V (D2)	–	–

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Author Profile

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Legal Mechanisms to Protect Great Artesian Basin Springs: Successes and Shortfalls

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Abstract

The community of native species dependent on natural discharge of groundwater from the Great Artesian Basin (GAB) has been listed as a threatened ecological community under Australia's main environmental law, the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act) since 2001. This paper introduces the ecological, cultural and legal context of spring management in Australia under the EPBC Act, and presents three ways that the community listing has advanced the conservation of GAB springs. First, listing provides heightened recognition and protection of the values of GAB spring communities. Second, it enables the protection of many species (the entire community) quickly. Third, it offers protection to a large, fragmented ecological community that would be difficult to protect solely by elements of the Australian protected area network, such as national parks and other types of national estate. The paper then highlights four complexities associated with the application of the EPBC Act to the management and conservation of GAB springs: the high level of discretion in decision making; data deficiencies that make it difficult to determine whether impacts are sufficiently "significant" to trigger assessment via an environmental impact statement (EIS); the flaws in offset management and mitigation measures; and the fact that community listings may not adequately protect individual species. A recent case study of the Doongmabulla Springs (central Queensland) illustrates how these legislative complexities were addressed under the requirements of the EPBC Act in relation to development of a major coal mine in their vicinity. The paper concludes with recommendations to enhance the capacity of the regulatory framework to conserve GAB spring species, communities and ecosystems.

Keywords: environmental law, groundwater, groundwater-dependent ecosystems, legal protection, springs, threatened species

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Introduction

Since the 1970s, understanding of the Great Artesian Basin (GAB) system has shifted and evolved, knowledge regarding the hydrology and geomorphology of GAB springs has advanced, and understanding of processes that may threaten the values of artesian springs has expanded (Andersen et al., 2016; Clifford et al., 2020; Peck et al., 2020). In addition, GAB springs have been afforded legal recognition under Australia's main environmental law, the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act) since 2001, through their listing as the "community of native species dependent on natural discharge of groundwater from the Great Artesian Basin" (Fensham et al., 2010). This paper provides an opportunity to reflect on the efficacy of the legal mechanisms available to regulate spring management and conservation.

The paper begins with an overview of the ecological, cultural and legal context of spring management in Australia, to set the context for reflections

on the efficacy of the EPBC Act. It presents three ways the conservation of GAB springs has been advanced by virtue of their listing as a threatened ecological community (Fensham et al., 2010). The paper then highlights four current complexities in the application of the EPBC Act to conservation of GAB springs. These legislative complexities are illustrated by a recent case history – the Doongmabulla Springs (central Queensland) – and the assessment of potential impacts from development of a major coal mine in their vicinity. The paper closes with recommendations to enhance the capacity of the regulatory framework to conserve GAB spring species, communities and ecosystems.

The Environmental, Indigenous Cultural Heritage and Legal Context of Spring Management in Australia

Environmental Context

Globally, groundwater and groundwater-dependent ecosystems are under-appreciated, under-managed and under-conserved (Famiglietti, 2014; Cantonati et al., 2012). Unlike surface rivers, impacts and declines in these ecosystems easily go unnoticed due to their hidden underground water flows, or accumulate slowly over time due to the long residence time of water in many aquifers. Groundwater-dependent ecosystems (GDEs) provide vital water and wetland habitat in areas with prevailing arid conditions (Davis et al., 2017; Stevens & Meretsky, 2008). In some of these systems, like the Australian springs dependent on the artesian waters of the Great Artesian Basin (GAB), their unique geological and ecological history has led to their designation as hot spots for aquatic biodiversity (Rossini et al., 2018). The system of springs provides permanent water in the arid zone for species that span the deserts, and vital habitat for species that are found only in GAB springs (Fensham et al., 2011). These endemic species generally have very limited geographic ranges; most live in just a few springs (in some cases even a single coffee-table-sized pool) in a single geographic location, usually less than 20 km^2 in area (Rossini et al., 2018).

As a result of their evolutionary history, many species living in springs differ from other Australian aquatic species in their limited capacity to adapt to water scarcity. In the Australian arid zone, many freshwater systems have become increasingly ephemeral since the Pleistocene (e.g. the Lake Eyre Basin). Most species that live in arid zone rivers and wetlands have adapted to this impermanence – they can disperse over great distances between connected waterbodies (e.g. fishes like the spangled perch, *Leiopotherapon unicolor* (Arthington & Balcombe, 2011; Kerezsy et al., 2013)), or can diapause within the sediment (e.g. tadpole shrimps, *Triops australiensis* (Brendonck, 1996)). However, the species found only in springs (i.e. endemic to GAB springs) are different. They have never developed traits for enduring water impermanence because they evolved in a system that has provided stable wetland habitats since the Pleistocene. Instead, they are habitat specialists that live nowhere but in GAB springs and rely on the environmental stability of this groundwater-fed system (Rossini et al., 2017). Although there is some variation in flow across the artesian basin, or in wetland extent on the ground (White et al., 2016), springs that support the highest biological diversity are those that are deep and maintain strong flow to support a permanent pool of water (Rossini, 2018).

The permanence of the water that feeds GAB springs, and therefore that maintains the habitat needed by endemic spring species, has been compromised since colonial expansion into the inland of Australia (Fairfax & Fensham, 2002; Fensham & Fairfax, 2003). The sinking of bores in the GAB began in the late 1880s, and the installation of large numbers of unrestricted flowing bores (reportedly 18,000 (de Rijke et al., 2016)) significantly reduced basin pressure (Habermehl, 2020; Brake, 2020), eventually causing reduced spring discharges and the dormancy of many springs (Fensham et al., 2016a; Powell et al., 2015). Alongside these declines, springs were impounded or excavated, and the activities of introduced species, including livestock, in and around springs have diminished habitat quality (Fensham et al., 2010). In addition, resource extraction, particularly for coal seam gas, has seen another wave of impacts on artesian pressure in the GAB and changes in water quality (de Rijke et al., 2016). Due to the significant impacts of these processes and changes to the unique assemblage of species that rely on GAB springs, the "community of native species dependent on natural discharge of groundwater from the GAB" was listed as a threatened

ecological community in the endangered category under the EPBC Act on 4 April 2001 (Fensham et al., 2010).

Indigenous Cultural Heritage

Springs are of great cultural significance to First Nations peoples of Australia (Moggridge, 2020). Spring waters sustained Indigenous peoples along trade routes throughout Australia (Aldumairy, 2005), are of symbolic significance in Dreamtime stories and folklore, and are critical to other cultural practices such as ceremonies (Robins, 1998; Mudd, 2000; Powell, 2012; Martin & Trigger, 2015; Powell et al., 2015). Studies in other parts of Australia show that First Nations peoples hold an extensive knowledge of the location and character of springs. For example, a study in a south-western area of the Northern Territory, undertaken in consultation with First Nations communities, reported that they were able to identify hundreds of water resources, including seepages, river pools, cave pools and soaks, that were not known to non-Aboriginal people (Hatton & Evans, 1998).

The connection of First Nations peoples to spring systems is mainly reflected in the Western legal system of Australia through their recognition as registered cultural heritage, which is generally regulated under state and territory laws, such as the *Aboriginal Cultural Heritage Act 2003* (Qld), and through the Native Title framework (*Native Title Act 1994* (Cwth)). The Native Title framework establishes a requirement for those who seek to affect the connection of a Native Title holder with a spring system, or other cultural or environmental value, to enter into an Indigenous Land Use Agreement. Nationally or internationally recognised cultural heritage matters, and recognised cultural heritage on land owned or managed by the Commonwealth, are afforded recognition through the EPBC Act.

The recent *Human Rights Act 2019* (Qld) also provides relatively strong recognition of the cultural rights of Aboriginal and Torres Strait Islander peoples, including the right "to maintain and strengthen their distinctive spiritual, material and economic relationship with the land, territories, waters, coastal seas and other resources with which they have a connection under Aboriginal tradition or Island custom"; and "to conserve and protect the environment and productive capacity of their land, territories, waters, coastal seas and other resources" (*Human Rights Act 2019* (Qld), s28(2)(d,e)).

Legal Context

Various local, state and national laws come into play and regulate activities that may impact on springs, either as an environmental feature or with respect to the species inhabiting spring wetlands. The key national legislation relevant to springs is the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act, 1999) which regulates activities that will or may have a significant impact on matters of national environmental significance (MNES) listed under the Act. A spring may itself be a listed MNES as part of the community, or impacts to springs may be regulated where the spring is part of a protected area such as a World Heritage area, or the species inhabiting a spring may be a listed as a MNES. The impacting activity may also be relevant, e.g. if a spring system forms part of a "water resource" that may be impacted by a gas or mining activity, the impact may require EPBC Act assessment under the "water trigger" (2013 amendment to the EPBC Act).

Assessment, protection and prosecution under the EPBC Act regarding actions or activities that may affect springs rely on the determination of whether the activity is likely to have a "significant impact". Generally, a significant impact is defined as an action that creates a change in a listed species or community that is "important, notable or of consequence, having regard to its context or intensity" (COA, 2013; McGrath, 2005). Whether or not an action is likely to have a significant impact depends upon the sensitivity, value and quality of the environment that is impacted, and upon the severity, duration, magnitude and geographic extent of the impacts. When applied to threatened communities, impacts are only considered significant if they relate to a community listed under the EPBC Act as "critically endangered" or "endangered" (COA, 2013).

As noted earlier, the "community of native species dependent on natural discharge of groundwater from the Great Artesian Basin" is listed as an endangered ecological community under the EPBC Act. Examples of impacts that may be considered sufficiently "significant" to affect the GAB

spring ecological community and therefore require regulation under the EPBC Act include: impacts that reduce the extent of a community; fragment it; affect habitat critical to species within it (including changes to hydrology); change the composition of species within it; or interfere with its recovery (COA, 2013). For individual species, activities are regulated if they might have a significant impact on organisms in any listing category (i.e. critically endangered, endangered, vulnerable). Impacts considered significant for a single listed species relate to the listing level (with the most stringent criteria applied to endangered and critically endangered species) but generally concern impacts with potential to cause long-term decrease in the size of a population, reduce areas of occupancy, adversely affect habitat critical to the survival of a species, or interfere with the recovery of the species (COA, 2013). For current listings of some GAB spring species, see Kerezsy (2020) and Rossini (2020).

Once a species is listed in an EPBC threatened species category, the Australian Government's Minister for the Environment may make or adopt and implement a recovery plan for that species. The aim of a recovery plan is to maximise the long-term survival in the wild of a threatened species or ecological community. The development of a recovery plan is not mandatory, but once developed and approved under the EPBC Act, Australian Government agencies and all other parties must act in accordance with the plan. A recovery plan should assist assessing officers when considering how to assess and impose obligations to mitigate impacts on a species, and it must not be contravened by a Commonwealth agency action. A recovery plan has been established for the community of native species dependent on natural discharge of groundwater from the GAB (Fensham et al., 2010).

Other state legislation may also seek to protect and/or regulate impacts on spring ecological communities and spring species. For example, the "Artesian springs ecological community" at the southern margin of the GAB in north-western NSW is listed as endangered under the *Threatened Species Conservation Act 1995* (NSW). In Queensland, certain springs in discharge areas of the Great Artesian Basin, but not those located in Tertiary aquifers, are classified as "defined regional ecosystems" and listed as endangered under the *Vegetation Management Act 1999* (Qld) (VMA) (Nelder et al., 2017). For example, under the VMA, Regional Ecosystem 2.3.39 includes spring wetlands on recent alluvium, Regional Ecosystem 4.3.22 includes springs on recent alluvia and fine-grained sedimentary rock/shales, and Regional Ecosystem 6.3.23 includes springs on recent alluvia, ancient alluvia and fine-grained sedimentary rock/shales (Nelder et al., 2017). Various other state and territory water laws, such as the *Water Act 2000* (Qld), the Queensland Great Artesian Basin and other regional aquifers water plan (GABORA) and the Water Sharing Plan for the NSW Great Artesian Basin Groundwater Sources 2008 (NSW), regulate groundwater extraction and activities that may affect groundwater, such as mining and agriculture. As with the EPBC Act, species in a spring community may be listed as a regulated species under state or territory environment laws.

Positive Outcomes from Legal Protections

The following section presents three ways that listing under the EPBC Act has advanced the conservation of GAB springs, the focus of this paper.

Recognition of the Value of Listed Communities and Species

The designation of MNES under the EPBC Act means that spring sites, species and communities are afforded more attention and recognition than other environmental sites, species or communities, with the intention that their listing may lead to protection and recovery. A MNES listing provides the following opportunities:

- When a native species or ecological community is listed as threatened under the EPBC Act, a conservation advice must be prepared and published. A conservation advice provides information, prepared by the Threatened Species Scientific Committee (TSSC), regarding the status of, and threats to, the species or community at the time of listing (EPBC Act, 1999, s266B(1)).
- A recovery plan or a threat abatement plan may be prepared and published for the species or system on the recommendation of the TSSC; both plans are intended to provide a framework for recovery activities. Where provided,

a recovery plan and threat abatement plan cannot be contravened by a Commonwealth agency in their decisions or actions (EPBC Act, 1999, s268 and s269).

- The triggering for assessment of any activity that may have a "significant impact" on the species, community or water resource, which may lead to the activity's rejection, approval, or approval with conditions to mitigate the impacts (EPBC Act, Chapter 2).

If a species, community or water resource is not listed as a MNES, it will not obtain the benefit of these opportunities for protection and recovery.

Protection of Many Species Quickly

The process by which a species is listed as threatened under the EPBC Act is thorough and can take a long time. It requires the committed collection, analysis and assessment of data for the species of concern, the submission of documentation to the Australian Government Minister for the Environment (the Minister), the assessment of that documentation by an expert panel, and the eventual preparation of listing advice and a recovery plan. To prepare listing documents, those with experience estimate that it takes approximately a year, if not more if the species is awaiting taxonomic description or revision. Following submission of the proposed matter for listing, the Minister must decide whether or not to list the species (EPBC Act, 1999, s194Q); the current turnaround post-submission can be many years. In comparison, through listing the entire ecological community of species dependent on natural discharge of groundwater from the GAB, over 100 spring species were protected in a single process. This highlights the power and increased efficiency of the community listing (Beeton & McGrath, 2009).

A further advantage is that the listing of species within a protected community automatically includes those of putative species status, whereas it is difficult to list an organism of uncertain taxonomic status individually. The GAB springs community listing also inherently acknowledges the interconnectedness of the constituent species, by virtue of their mutual dependence on natural discharges of groundwater. Furthermore, a reduction of spring "habitat" critical to species living within it (including changes to hydrology) is considered a significant impact under the EPBC Act.

Complementarity Between Protected Areas, Community Listing and Individual Species Listings

Listing of the GAB springs community as endangered under the EPBC Act has the potential for protection of a large, fragmented and complex system that would be difficult to protect solely by elements of the Australian protected area network, such as national parks and other types of national estate. Some high-value springs are currently protected as part of a larger national park (e.g. springs within the Eulo complex; see Peck, 2020), some in their own park (e.g. Irrawanyere/Dalhousie) or conservation area (e.g. Elizabeth Springs or the Edgbaston portion of the Pelican Creek complex). However, the majority exist as small pockets within large properties under pastoral lease. Excising these areas would likely be a protracted and politically contentious exercise (nor is it necessarily the most efficient approach) and would place a significant strain on each state's nature conservation resources.

By listing springs under the EPBC Act, each spring complex is offered some form of legally binding protection from adverse impact, irrespective of the jurisdiction and ownership of the landscape it falls within. Any listing of species in addition to their inclusion in the community listing, or protection of their range within a protected area, complements this EPBC listing. The EPBC listing should also protect springs from impacts in areas outside of an annexed conservation area – a protective mechanism that would not typically occur if the entire community were not listed.

Complexities in Applications of the EPBC Act to GAB Springs

Determining Significant Impacts in Data-deficient Systems

When an activity is proposed that may have a significant impact on a MNES, it must be referred to the Australian Government Minister for the Environment (the Minister) for consideration under the EPBC Act. If impacts associated with the activity are deemed sufficiently "significant" to trigger assessment, it is designated as a "controlled action", which requires an environmental assessment and

approval. The proponent is informed of the level of environmental assessment that must be undertaken, i.e. whether a full environmental impact statement (EIS) is needed or whether the assessment can be prepared from "preliminary documentation" already provided to the environment department. The data collected and analysed for the environmental assessment are prepared or commissioned by the proponent and submitted to the department for assessment.

Even in a perfect scenario, where a proponent diligently prepares an assessment and that assessment is critically and independently reviewed, the determination of what constitutes a significant impact, whether it will occur, and what its outcome will be, all rely upon robust data. Such determinations are challenging in data-deficient systems.

Western systems of spring science and conservation are less than 50 years old and have not drawn on the knowledge obtained by First Nations peoples over many thousands of years (de Rijke et al., 2016). The first basin-wide database of GAB spring locations has been available for only two years (DSITIA, 2015). Surveys are still documenting the locations of springs (Powell et al., 2015; Silcock et al., 2020). Ecologists are describing new species found only in GAB springs at a rate of two per year (Rossini et al., 2018), a rate highly contingent on research funding. Understanding of the natural spatial and temporal variance of spring environments is emerging (Rossini, 2018; White et al., 2016), yet the taxonomy of many spring species remains unresolved (Murphy et al., 2009), and knowledge of their habitat requirements is limited, particularly for invertebrates (Rossini, 2020). These data deficiencies are not unique to GAB springs; they are a ubiquitous ecological reality in freshwater ecosystems. In high-risk areas such as springs, with high levels of endemic diversity, and where levels of exposure to threats and their consequences are poorly understood (Andersen et al., 2016), data deficiencies are of deep concern and must be remedied, or at least accommodated during assessments of "significant" impact. Under the EPBC Act, where there is scientific uncertainty about the impacts of an action or activity and the potential impacts are serious or irreversible, the "precautionary principle" is applicable. "Accordingly, a lack of scientific certainty about the potential impacts of an action will not itself justify a decision that the action is not likely to have a significant impact on the environment" (EPBC Act). Even so, significant impacts may be under-estimated or options and activities to prevent, minimise or even meaningfully monitor impacts could be challenged.

Coping with data deficiencies raises another dilemma in the assessment framework under the EPBC Act. In the current Australian legislative system, the reality of progressing approvals of activities or projects in a data-deficient system is generally accommodated by requirements ("conditions") being placed on projects, which may provide for implementation of an adaptive management framework as the context for monitoring. Such a stipulation on a project is regularly used in replacement of a full understanding of the system, its ecology and species composition prior to approving an activity that may cause impacts (Lee, 2014; Lee & Gardener, 2014). Adaptive management is an impact management approach that requires iterative monitoring and adjustment of activities in response to the results of constant hypothesis testing (Stankey et al., 2005; Williams, 2011). In applied terms, this means that the assessment of impacts relies on the proponent's willingness and ability to assess and monitor outcomes with scientific rigour post-approval, and to adapt activities quickly and proactively to avoid or mitigate impacts as they become apparent. It relies on the regulatory infrastructure to enforce these conditions and force responsive action, along with a requirement on the proponent to report regularly and transparently on the evolving impacts of their activities and any changes that were not predicted. Adaptive management also relies on the assumption that impacts can be avoided or activities can be adjusted or changed once any impacts have been discovered. The capacity to avoid impacts cannot necessarily be known or predicted if the potential impacts or environmental features and processes, such as the connectivity pathways between aquifers, are not well understood at the time of approving the activity (Currell et al., 2017).

This is also particularly problematic when the package of "conditions" and performance indicators for a project are established at the approval stage, despite a lack of full understanding of how an impact may manifest. Adaptive management, in an effective sense (i.e. one that safeguards against

significant impacts), requires as much upfront understanding as possible, including rigorous design of monitoring, empirical testing of hypotheses, and an ability to test and model how a response will influence an outcome (Chades et al., 2012; McLain & Lee, 1996). Adaptive management in practice rarely occurs in this form, and there are few mechanisms to ensure that it must do so under the EPBC Act (Lee, 2014; Lee & Gardner, 2014).

Regulatory environmental assessment is only able to achieve the general aim of mitigating or avoiding environmental impacts effectively if reliable, fulsome data are available and provided at the time of assessment. Furthermore, such data must be available for scrutiny and ongoing monitoring, and impact assessment processes should be accountable and transparent to the public. However, even if these requirements are met and applied effectively under the current mandates of the EPBC Act, they cannot be applied to a great deal of historical development for farming and mining which was deemed fully approved at 16 July 2000 when the EPBC Act commenced (McGrath, 2005).

Ministerial Discretion

If a significant impact is predicted to occur and the project is referred under the EPBC Act, the Minister must decide that the activity is a controlled action (EPBC Act, 1999, s75(1)(a)) and state the MNES that must be considered in the assessment of the activity (EPBC Act, 1999, s75(1)(b)). There is also an option to declare at the time of referral that the project is clearly unacceptable and that approval be refused (EPBC Act, 1999, Part 7, Division 1A). After assessment, the Minister may decide to refuse to approve the activity, or to approve the activity with or without conditions associated with the approval to mitigate the impacts (EPBC Act, 1999, s133), including by requiring that the impact be offset. The Minister has the discretion to determine which of these paths is taken. Mitigation and offsetting procedures are addressed below. This section deals with activities that cause "significant" impacts, which should, technically, render them illegal under the EPBC Act.

While the Minister may refuse an activity under the Act, this option is very rarely used. As at 2015, 20 projects had been either deemed "clearly unacceptable" or were refused after assessment (Macintosh et al., 2017), being 0.36 per cent of the total projects referred between 2000 and 2015 (5495). A recent example of the issues that may arise where environmental assessment includes broad Ministerial discretion arose in the widely reported and criticised Commonwealth Government approval of the Groundwater Dependent Ecosystem Management Plan for the highly contentious Adani Carmichael Coal Mine (Currell, 2016; Currell et al., 2017).

In a hypothetical system where it appeared that the proponent did not provide adequate data in their assessment of impact, or the Minister approved an activity for which strong evidence suggests there will or will likely be an unsustainable level of impact on a MNES, challenging an approval remains the responsibility of the public; however, recourses are limited. It is common at a state level for development laws to provide the public with the right to apply for a "merits review" of a development decision. A merits review provides an independent court analysis, free of politics, where the court stands in the shoes of the decision maker and decides whether the correct decision was made, given the evidence before the decision maker and the requirements of applicable law. This option is provided in many environmental and planning decision frameworks in recognition of the significant risks of corruption in development decision making, which has been recognised by the Productivity Commission and the NSW Independent Commission Against Corruption, as well as through the work of the Australian Panel of Experts on Environmental Law (APEEL) in their recent review of reforms needed to improve environmental governance in Australia (APEEL, 2017). Under the EPBC Act, at present, there is no right for the public to apply for a merits review of a Ministerial decision, or to apply for a review whether the decision was appropriate based on the evidence available, e.g. with respect to the level of impact deemed allowable. The public may only seek judicial review as to whether legal procedures were correctly followed according to the EPBC Act; this is a much more limited form of administrative review (McGrath, 2008). If a court case is correctly brought demonstrating illegality in the process followed during an impact assessment, the decision maker and proponent will typically start the process again and remake the decision.

If an activity is found to have a significant impact after going ahead, but was not referred for assessment, it is up to the proponent to refer it to the Commonwealth Government, or the state or Commonwealth Government to require referral, or the Commonwealth Government to take enforcement action. In most cases, any monitoring of the activity's impacts on a MNES is undertaken in a way that is not transparent to the public and may not be reported regularly to the government regulator. The lack of transparency in monitoring impacts is thus a limitation on the ability of the government and the public to demonstrate whether significant impacts have occurred that were not approved under the EPBC Act, and therefore whether enforcement action is required.

The APEEL review has noted the flaws in environmental laws and governance frameworks that expose environmental decision making to risks of bias and the favouring of development over environmental protection (APEEL, 2017). The APEEL report, *Blueprint for the Next Generation of Environmental Laws in Australia*, provides a list of recommendations for improving issues found with environmental governance in Australia that are degrading the state of the environment; these include the establishment of an independent Commonwealth Environmental Protection Agency to administer Commonwealth environmental laws (APEEL, 2017).

In addition to the risks around development bias raised by the lack of strong accountability measures around decision making under the EPBC Act, others have also identified weaknesses in enforcement of the Act. The 2009 Hawke Report review of the EPBC Act noted that compliance and enforcement activities had been limited, and recommended that the government should allocate substantially more resources to compliance and enforcement activities, and make wider use of the range of compliance and enforcement options available under the Act (Hawke, 2009). Moreover, in 2018 an independent review of the EPBC Act's interaction with the agricultural sector, commissioned by the Commonwealth Government, found that many agricultural operators were still not aware of their obligations under the EPBC Act, nor how to address those obligations (Craike, 2018).

Community Listing May Not Protect Individual Endemic Species

When a project's potential impacts are being assessed, one of the first steps is to determine whether the site provides habitat for threatened species. In reference to GAB springs, there is a high likelihood that the area will provide essential habitat for numerous species listed within the endangered "community of native species dependent on natural discharge of groundwater from the Great Artesian Basin", and some of those species may be listed individually under the Act.

As discussed previously, multiple listing frameworks relate to the GAB springs system – for example, a species can be listed at a Commonwealth level or at a state level, either as a component of the listed endangered community or as an individual protected species, and each state can hold a different threat listing level for the same species. Other forms of listing are purely advisory, e.g. the IUCN Red List of Threatened Species (IUCN, 2012). For these listing frameworks to adequately protect the species endemic to GAB springs, they must satisfy two requirements.

First, in an ideal scenario, the full diversity of endemic species would be documented, and all GAB endemic species would be protected as part of the endangered community by being named within the community description. In addition, for species whose persistence is particularly threatened (i.e. they are found at only one spring complex, show declining population trends or are exposed to multiple interacting threats), an individual listing would be in place at Commonwealth level and subject to conservation advice, recovery advice and assessment of potential significant impacts on the species. Preferably, such a species would be listed at the same level of endangerment by all jurisdictions within which it is found, and with equivalent protections from impact. Additionally, such a listing, and the related documents such as the recovery plan, need to be informed by sufficient information on the distribution and ecology of the species (which usually relies on time-series of data), as well as evidence of a threatening process, to support the claim of decline. An example of such a species is the red-finned blue-eye, *Scaturiginichthys vermeilipinnis* (Fairfax et al., 2007; Kerezsy et al., 2020), although there are still discrepancies in

the level at which it is listed (Australia – endangered; IUCN – critically endangered). This tiny fish benefits from management actions focused on protecting the biodiversity of GAB springs biota as a community, but its individual species listing status also means that targeted actions focused on its recovery are in place (Kerezsy, 2020).

Unfortunately, most species that rely on GAB springs are not included in the present community list, and many of those exposed to high risk of impact or even extinction do not have complementary individual listings, e.g. many invertebrate taxa. This broad group represents about 85% of the species known to be endemic to GAB springs; however, this is probably an underestimate as the number of species in some major groups is poorly documented at basin scale (e.g. the Ostracoda (Rossini et al., 2018)). Most of these species have different listings across state, Commonwealth and IUCN listing frameworks (Rossini, 2020). For example, the undescribed species of *Glyptophysa* from the Pelican Creek complex of springs has a distribution as limited as the red-finned blue-eye, is exposed to similar threats, and shows evidence of decline, but remains unlisted anywhere apart from the GAB springs endangered community, where it is listed as an undescribed species (Rossini, 2018).

Relying solely on the community listing is therefore not sufficient, primarily due to three key constraints: a lack of data about a particular spatial area; a lack of taxonomic and distribution data about a single species; and the time between description and action. First, a lack of taxonomic data and refinement means that the full complement of taxa that should be included in the community listing is incomplete. In some cases, this relates to species yet to be discovered and can mean that an impact assessment for a particular site assumes there are no endemic species present. For example, the Moses Springs complex was thought to contain only one endemic species until further detailed survey effort expanded the list. Second, a similar constraint relates to taxonomic refinement within species already included in the description. For example, the endemic amphipod species of Kati Thanda–Lake Eyre were believed to be a single species with a broad distribution until a taxonomic revision (Murphy et al., 2009) revealed that amphipods are in fact a set of multiple cryptic species, each endemic to its own geographically limited area. When considered as a single species with a broad distribution under the GAB community listing, disturbance or extinction in one portion of that range may not be considered a "significant impact". However, a more refined understanding of species boundaries revealed that the same disturbance could affect the full extent of a narrow range species – a consequence that is clearly a "significant impact". Third, without ongoing monitoring of population trends of listed species, declines and extinctions may occur. For example, species of endemic snails from the Eulo complex were putatively listed in the community description in 2010, but a full taxonomic resolution was not completed until 2019 (Ponder et al., 2019). Within that decade, at least one of these endemic species has become extinct.

Offsets and Mitigation Measures

Under the EPBC Act, there is provision for significant impacts to be compensated under an environmental offset. The 2012 EPBC Act environmental offsets policy requires that, in assessing whether to require an offset, the nature and significance of the likely impacts on protected matters must be established, then whether the impacts are avoidable, and if not, whether impacts on protected matters can be mitigated. If neither of the latter is possible, an offset may be deemed to be appropriate to help compensate for significant residual impacts (Australian Government, 2012).

There is little clarity around when an impact should be considered avoidable. This must be determined with respect to whether the activity or project is important enough to be allowed to proceed in spite of the significance of its impacts, and then, if allowed, whether the activity should be located or undertaken in such a way that the impact is avoided.

As to the first element of this consideration, the low level of refusals given to projects referred under the EPBC Act (Reside et al., 2019) puts into serious question how much weight is being given to the test of whether the importance and need for the activity is sufficient to warrant its potential impacts. As to mitigation, there is limited guidance as to how impacts on springs should be mitigated and whether this is hydrologically or ecologically possible. For example,

in regard to springs, the Bioregional Assessment Program (Lewis et al., 2018) set acceptable limits for groundwater decline in the Galilee Basin using expert elicitation. However, these limits operated under three assumptions:

1. That experts could define which species within the GAB listed ecological community were actually present.
2. That they had sufficient knowledge and data to comment on impacts of groundwater decline to said species.
3. That there was enough collective knowledge regarding the connection between water extraction volume, surface manifestation and ecological consequences to set acceptable limits to groundwater decline.

Where extractions are approved, mitigation efforts such as reinjection technologies are being tested by some proponents (DSD, 2015). These technologies can be risky and have been associated with groundwater contamination (Prommer et al., 2016).

The recourse to offsets has attracted many critiques (Gibbons & Lindenmayer, 2007; Gordon et al., 2015; Maron et al., 2015), and in the GAB springs context they are particularly problematic. There are two key reasons for this. First, the system is not spatially homogeneous, so it is typically not possible to find areas to offset that are equivalent to the impact site. The system is naturally fragmented, and patches of the endangered community have existed and functioned, and continue to exist and function, as what could technically be considered 33 separate and discrete communities (Rossini et al., 2018). Despite some complexes containing the same species, each contains a distinct 'evolutionary unit', as spring complexes and the populations they contain have been separated for millions of years with no gene flow between them. With further investigation, many of these populations have later been classified as comprising separate species (Murphy et al., 2009; Murphy et al., 2013). The loss of diversity or of threatened species populations from one locality typically cannot be offset by the preservation of the GAB community or by a population of a species at another locality. Second, the groundwater dependency of GAB springs dictates where suitable aquatic habitat is found, and its spatial extent. Restoration and revegetation efforts aimed at establishing an offsetting for an impact site will be limited to locations where water naturally discharges as springs already supporting their own unique portion of the threatened community. Unlike other offsetting examples, where a forest patch can technically be extended and restored to replace that lost through impact to yield no net loss of habitat, it is impossible to replicate or expand the GAB dependent springs habitat in areas without a natural geological conduit of water flow and strong natural discharge from the basin.

This situation alludes to another major constraint in the way decisions are made regarding impacts on GAB springs and the use of offsets. Wetlands of this system occur across a huge scale and rely on a groundwater source of great complexity. If mitigation and offsets are assessed on a case-by-case basis – a few springs or a spring complex or two at a time – the cumulative impact of many projects could be a system-wide collapse via 'a death by many cuts'. Like a surface-water basin, the GAB is a large, multi-jurisdictional, linked but complex system of groundwater that is essential for the persistence of springs. Impacts in one location may affect groundwater flows in areas beyond the impact site, and have cumulative impacts on water resources that are not well understood and notoriously poorly regulated (Nelson, 2019). If each project's impact on the GAB is assessed individually, all decision outcomes – no significant impact, avoidance of impact, mitigation or offsetting – are possible. Multiple projects, each assessed as having minor impacts, could be approved and their cumulative impact on groundwater pressure and spring habitats could be significant (Nelson, 2019). At some point, as more and more water is extracted by each project, the system may reach a threshold of water or pressure loss, reduced recovery capacity and ecological collapse.

Some protective provisions have been introduced into the EPBC Act by defining impacts on "water resources" associated with coal seam gas and large coal mining, thereby creating a "trigger" for referral of any project impacting surface or groundwater (Currell, 2016). However, assessment of impacts under the water trigger holds similar flaws to those detailed above for listed species, such as a lack of clear guidance on when impacts must be avoided. At present, cumulative impacts are not required to

be considered or avoided under the framing of the EPBC Act. They can be required to be considered under an EIS via terms of reference, but there is no requirement to avoid them and no component within the EPBC protocols for assessment that accounts for them. Proposed activities are assessed individually for their impacts on the environmental values potentially directly affected by the activity, rather than with reference to the overall impacts on a MNES species or community from the multitude of impacts that may have occurred or be otherwise proposed to occur.

A Case Study: Doongmabulla Springs

An open cut and underground thermal coal mine, the Adani Carmichael Coal Mine Project (the project), has been proposed for a site approximately 11 km from the Doongmabulla Springs north-west of Emerald in Central Queensland. This mine has received approval from the Queensland and Commonwealth governments to produce 60 million tonnes of coal per year for 60 years. The mine proponents are Adani Mining Pty Ltd and Carmichael Rail Network Pty Ltd (joint proponents), both wholly owned subsidiaries of Adani Australia, part of the Adani Group. The assessment of this particular mine offers an interesting case study demonstrating how potential impacts on spring systems have been assessed in Australia. It illustrates how the legislative complexities discussed above were addressed under the requirements of the EPBC Act.

The project was declared to be a "coordinated project" under the *State Development and Public Works Organization Act 1979* (Qld) whereby the Coordinator-General of Queensland coordinates the various assessment processes for the project. The project was referred to the Commonwealth Environment Minister under the EPBC Act and declared a "controlled action" requiring assessment via an environmental impact statement (EIS). Through the coordinated project declaration, the proponent was able to undertake one EIS that served the purposes of assessment under both the EPBC Act and the *Environmental Protection Act 1994* (Qld). Through the EIS process the proponent indicated that the project may impact the Doongmabulla Springs.

The Doongmabulla Springs form a nationally important wetland system listed in the Directory of Important Wetlands in Australia (COA, 1993), a different and separate listing system from MNES under the EPBC Act. The springs are dependent on regional groundwater, but to what extent they depend on Great Artesian Basin groundwater is debated (Fensham et al., 2016b). Regardless of the extent of their connection to the groundwaters of the GAB, the Doongmabulla Springs are home to a variety of native plant and animal species that also live in the GAB springs, and are therefore included in the listed endangered community of organisms dependent on natural discharge from the GAB. Species common to the Doongmabulla Springs and GAB springs include at least six species of plants, two species of invertebrates of yet-to-be-confirmed endemic status, and a range of associated groundwater-dependent wetland types such as groundwater-dependent forests.

The site of the Doongmabulla Springs is of significance to the Traditional Owners of the land, the Wangan and Jagalingou People, the springs forming part of the Clermont-Belyando Area Native Title Claim (QC2004/006). This application was first filed in the Commonwealth Court on 27 May 2004 by the Wangan and Jangalingou claimants, and listed on the Register of Native Title Claims on 5 July 2004. As stated by the Traditional Owners, "[Adani] would permanently destroy vast swathes of our ancestral homelands and waters and everything on and in them, likely including our most sacred site, Doongmabulla Springs, from where our spiritual ancestor – the Mundunjudra (Rainbow Serpent) – travelled to shape the land. We also face the imminent and permanent extinguishment of our rights and interests in part of our ancestral homelands by the Queensland government and the transfer of tenure in those lands to Adani. Because our lands and waters embody our culture and are the living source of our customs, laws, and spiritual beliefs, their destruction by the Carmichael Coal Mine and the extinguishment of our rights and interests in a part of our lands will also destroy our culture" (Lyons, 2018; Lyons et al., 2017).

The proponent summarised the environmental values of both Doongmabulla and Mellaluka Springs in its EIS and highlighted that there is sufficient evidence to suggest there are more endemic species at Doongmabulla than currently described (Adani Mining Pty Ltd, 2012, pp. 2–7). Post approval of the

project, the groundwater modelling that underpinned assessment of potential impacts was challenged and the opposing interpretations of groundwater impacts were scrutinised. The currently accepted revised EIS sets an acceptable groundwater drawdown of up to 20 cm as the level at which springs could be safeguarded against adverse effects. The EIS also stipulates timelines of response to potential impacts, in which case a cease work order must be put in place and the timeline for impact reporting and review must be stated.

This case study exemplifies the four key complexities in applications of the EPBC Act to GAB springs outlined above.

Data Deficiency

This limitation was flagged continually during hearing of the Adani Carmichael Land Court mining objection, particularly regarding hydrogeology (Currell et al., 2017). Ecological uncertainty received less attention but is also critical. Debate continues as to the ecological impact that the set drawdown limit would have on spring water depth, habitat area, vegetation and the persistence of endemic and non-endemic taxa (Currell, 2016). The list of species endemic to the Doongmabulla complex grows and, at present, includes species of plants and invertebrates that remain undescribed. There is no provision in Adani's groundwater management plan (nor in the conditions associated with the project approval) to conduct taxonomic research into currently undescribed species or identify modes of gene flow between spring populations that are highly likely to be impacted or lost with the commencement of mining activity. This is a lost opportunity in the present regulatory frameworks, whereby proponents could be required to undertake the environmental assessment not only of possible impacts on listed MNES, but also to provide an assessment of any species within the development site that may be impacted. This requirement would greatly assist data collected on aquatic and other species around Australia.

Significant Impacts

The proponent predicts no significant impact on springs (Adani Mining Pty Ltd, 2012). However, it can be argued that if a 20 cm drawdown occurs, then the following significant impacts, as listed in the significant impact guidelines, will arise: reduced extent; increased fragmentation; adversely affected habitat critical to survival; modification or destruction of factors necessary for survival (such as water); substantial changes in species composition; and interference with recovery of an endangered ecological community.

The party responsible for monitoring and reporting such impacts at present is the proponent. Long-term viability of the community of species endemic to GAB springs that are restricted to the Doongmabulla Springs currently rests heavily on the proponent's ability to:

(a) identify a trigger for any of the potential impacts listed above as a result of the project's resulting groundwater decline;
(b) rectify that impact and decline very rapidly, because endemic species in this system, like the endangered pipewort *Eriocaulon carsoni* and the gastropod *Gabbia rotunda*, are unlikely to survive more than 72 hours out of water (Rossini et al., 2018); and
(c) leave the site post-impact in the original groundwater and ecological state.

Stronger conditioning of monitoring and adaptive management frameworks, public and expert access to ecological impact reporting, and the potential for expert surveys to provide assurance and support to proponent-led assessments of impact, would all provide greater assurance that the Doongmabulla and Mellaluka Springs will not be significantly impacted by mining activities and groundwater drawdown.

Ministerial Discretion

Thanks to intensive media coverage of this case, the role of Ministerial discretion in relation to project approvals under the EPBC Act and associated risks can be observed in this matter. The timing and processes put into play for the approval of the Carmichael Coal Mine at both Commonwealth and state level around the time of the 2019 Commonwealth Government election cast a shadow over the legitimacy of the assessment and approvals for this project. Public outcry and comment regarding the project continues. For example, despite the claim that the groundwater and monitoring protocols for this project

have received full scientific support, it has been reported that no such approval was categorically given by the independent scientists whose advice was sought, and it has been suggested that the decision was rushed (Slezak, 2019). The modelling for Adani's Groundwater-Dependent Ecosystem Management Plan (GDEMP) may have underestimated the effects of groundwater drawdown on the springs – a critical issue for the future of these groundwater-dependent ecosystems. Currell et al. (2017) conclude that: "Despite the large scale of the project, it appears that critical scientific data required to resolve uncertainties and construct robust models of the springs' relationship to the groundwater system were lacking at the time of approval, contributing to uncertainty and conflict."

Furthermore, numerous concerns have been raised around the proponent's compliance with approvals thus far, including a recent legal action commenced by the Queensland Government for false and misleading information as to tree clearing undertaken and reported in the proponent's annual report (Willacy & Blucher, 2019). The Queensland Government has taken legal action and served infringement fines against Adani for illegal discharge of contaminated water into wetlands adjacent to Abbot Point (EDOQ, 2019).

In a perfect system where the Minister, consulting scientists and the proponent act ethically, professionally and according to due process, this feature of project assessment under the EPBC Act would be of little concern.

Mitigation and Adaptive Management

The Adani Carmichael Coal Mine Project (EPBC 2010/5736) was conditioned through the EPBC Act to implement an annual Great Artesian Basin offset measure at least three months prior to commencement of mining operations. The relevant conditions involve returning at least 730 megalitres per annum for a minimum five-year period from commencement of excavation of the first box cut, to offset the predicted annual water take associated with the action.

A heavy weight is placed on the proponent's ability to respond to triggers of groundwater decline. At present, the planned corrective actions for groundwater drawdown exceeding 20 cm (a risky estimate of acceptable drawdown) are vague. Adani states that a drawdown trigger will lead to "further mitigation activities with regards to water availability at the springs" (Adani Mining Pty Ltd, 2012), but does not state what these activities would involve. The proposed corrective actions outlined in the management plan do not necessarily require the cessation of mining activity and are not likely to be sufficiently rapid because they require research and planning under Section 25 of conditions attached to the approval, which will likely take considerable time and involve a lengthy process of review before actions are taken. This case study reflects the weaknesses in how the adaptive management cycle is being applied in environmental approvals currently, particularly for groundwater impacts from resource extraction, where impacts may be felt more quickly and severely than the management system can respond (Lee, 2014).

Recommendations

Australian spring complexes and ecological communities are unique, widely dispersed, disconnected and fragile, and still poorly documented and researched as GDEs. Any regulatory framework that seeks to protect spring complexes and their biological communities must recognise these fundamental characteristics and be responsive to them to ensure the survival of these ecological wonders. This analysis has sought to highlight how Australia's main environmental law, the EPBC Act and its regulatory framework, may not function effectively to achieve the protection of GAB springs and spring communities.

This paper has focused on the regulatory framework that seeks to protect the ecological value of springs and spring communities. It has not provided commentary on the implications of impacts on springs for First Nations people, or the legal mechanisms available to protect the cultural values of springs and related features. This significant issue is deserving of far more attention and analysis, yet one that extends beyond the specialist expertise of the authors.

Through this analysis of complexities in applications of the EPBC Act to GAB springs, the following recommendations are proposed to highlight legislative improvements that could be made to Australian environmental legislation to better protect springs and spring communities.

Ministerial Discretion

The significant discretionary powers held by the Australian Government Minister for the Environment under the EPBC Act can be exercised to achieve a balance between protection of the environment and benefits to developers. While the Minister may refuse an activity or project under the EPBC Act, this option is very rarely used; only 20 projects (0.36%) have been declined since the Act commenced (Reside et al., 2019). Under the EPBC Act, at present, there is no right for the public to apply for a merits review of a Ministerial decision. The public may only seek judicial review as to whether the legal process was correctly followed according to the EPBC Act – a much more limited form of administrative review (McGrath, 2008). To address this deficiency, APEEL (the Australian Panel of Experts on Environmental Law) recommended the establishment of one or more new independent statutory authorities to perform functions currently exercised by the Minister and other Commonwealth statutory environmental authorities (APEEL, 2017), as follows:

(a) An independent Commonwealth Environment Protection Authority that would be responsible for undertaking environmental impact assessment, auditing and approval for all development proposals for private and government related development (APEEL, 2017, Recommendation 2.14).

(b) A Commonwealth Environment Commission, to be responsible for administering strategic environmental instruments (which could provide for better cumulative impact assessment), conducting and making recommendations from environmental inquiries, and importantly, a nationally coordinated system of environmental data collection, monitoring, auditing and reporting, for particularly species and environmental features, as well as with respect to broader environmental sustainability indicators and trends.

(c) A Commonwealth Environmental Auditor responsible for monitoring and reporting on the performance of the Commonwealth regulatory bodies in relation to the performance of their statutory environmental responsibilities; and to recommend any necessary new strategic environmental instruments (APEEL, 2017, Recommendation 2.9(i)).

These new governance arrangements would be a significant step forward in environmental impact assessment, project approvals, conditioning, monitoring and reporting of the regulatory processes designed to protect the environment – in this case, threatened springs and groundwater-dependent ecosystems of the Great Artesian Basin.

Mandated Standards of Environmental Assessment

Environmental impact assessment is the most informative part of the approval process under the EPBC Act. An EIA must be informed by as much quality information as possible, and data gaps, competing conceptual models and points of potential scientific conjecture should be identified. This information and the assessment of potential impacts feed into decisions about the acceptability of a project.

Regulations should ensure that the assessment process is transparent and that decision makers and proponents are accountable. Standard procedures should also make provision for external review and comment, e.g. provisions for the public to be involved in and witness to the process through submission rights, access to information, and the ability to scrutinise decisions and evidence in an independent forum, such as a court via merits review.

Rigorous assessment of the ecological risks of extinction or decline in the listed GAB springs community and the cumulative hydrogeological risks of basin-wide pressure decline or alteration is essential. Environmental assessments should conform to mandated standards, as far as possible given the complexity of groundwater and ecological science, requiring:

(a) On-site surveying to best understand the characteristics of MNES potentially impacted by the proposed activity, including no less than mapping known extent of occupancy and habitable wetland area for spring endemic species; this would guide the development of hydrological models that can accurately predict the loss of habitat for each species.

(b) Provisions for supporting ecological and taxonomic research into any spring complexes where impacts will be likely to occur,

including precursory taxonomy, distribution and ecological requirements; this would help avoid data deficiency bias and loss of species that should be listed for protected status under the EPBC Act.

(c) Consideration of cumulative impacts, including impacts on the MNES that may occur from existing and approved projects that have not yet commenced.

(d) A basin-wide approach to assessment of impacts on springs. GAB-scale assessments of extinction risk, standardised impact assessment approaches that focus on species and hydrogeological processes, and standardised monitoring frameworks have been applied, or are in development. They should be mandatory for any project that triggers an impact on a groundwater-dependent ecosystem.

Standardised, Transparent and Publicly Available Assessment Methodology

Currently there is very little transparency around monitoring required under EPBC Act approval conditions and no central database for the collection and dispersal of data on MNES threatened by development projects. This lack of a centralised, transparent data repository is leading to environmental assessments which are not informed by all available data, and which are often heavily dependent on proponent-derived data and modelling. This is exacerbated in the current economic climate where there is little funding for ecological science to help build collective knowledge of environmental systems in Australia.

For systems where cumulative impacts are a risk, this is particularly pertinent. A centralised repository of environmental monitoring data will assist with independent review of any 'conditioned' proponent monitoring and modeling, as well as building overall ecological knowledge and understanding of impacts on springs at a GAB scale. It would enhance the quality of environmental impact assessment and decision making. To achieve this, the following developments are needed:

(a) A GAB spring specific assessment framework, as used for impacts on other significant MNES such as the koala.

(b) Standardised methods of MNES impact assessment, modelling of impact scenarios and monitoring frameworks.

(c) All projects monitoring spring impacts obligated to contribute data to the publicly available national springs database.

All environmental values and environmental impact assessment frameworks would be better protected from this initiative being implemented across all taxonomic groups, species and communities.

Stricter Rules Around the Conditioning of Project Approvals

Given the heterogeneity and naturally fragmented nature of the GAB springs system, the option of protecting equivalent systems or achieving net conservation gains through offsets seems unlikely. This will mean that decision frameworks at the approval stage and conditioning of approved projects must be founded on standardised and comprehensive data. The following recommendations warrant consideration:

(a) Inappropriate impacts on threatened species or communities must be avoided, with 'inappropriate' being determined by mandated thresholds of decline, or loss relevant to the viability of each species, or the number of species within the community.

(b) Providing an expert-approved compendium of standards as to the nature of appropriate mitigation strategies, and conditions for adaptive management monitoring and response.

(c) Minimising the use of offsets to compensate for unavoidable impacts, or setting conditions that require rehabilitation, where neither activity is realistically achievable, particularly in the case of GAB springs.

Enhancing the Water Trigger

The "water trigger" (2013 EPBC Act amendment) has provision for consideration of cumulative impacts. However, the EPBC Act does not require the Minister to refuse resource development on the basis that it will be associated with significant *cumulative* impacts. Thus, there is no opportunity for the public to be confident that a project will be refused due to significant cumulative impacts on a spring or spring community. Further, the

water trigger and the EPBC Act in general involve assessment on a project-by-project basis rather than strategic assessment of impacts at the scale of an entire catchment or water resource. This means there is limited assessment of the overall capacity of a catchment/water resource to support the accumulating impacts of several/many mining and other developments. Bioregional assessments are being undertaken in areas with significant coal deposits to determine the cumulative impacts of coal and coal seam gas development on water resources. This program is yet to result in amendments to the EPBC Act or other environmental legislation to provide for limits on cumulative resource development or statutory strategic planning for those areas.

The water trigger is also limited in its focus on coal and coal seam gas development and does not include water take that is incidental to the CSG or large coal mine activity, even though these activities can be directly linked and have equivalent impacts to those of the regulated activities. There is no rationale for limiting the water trigger to its present range of activities when any activity that may cause significant impacts on water resources and MNES should be assessed and avoided if found to be unsustainable. There is a good opportunity through the framework of the water trigger and the bioregional assessments to ensure that these initiatives lead to meaningful improvements in how springs and spring communities are protected under the EPBC Act, so as to ensure their survival into the future. The following amendments to the EPBC Act and its regulatory framework are recommended:

(a) Require that mining-related activity can be refused where there are significant cumulative impacts on a spring or spring community.

(c) Broaden the water trigger to include any activity that may have a significant impact on a water resource or water-dependent ecosystem, such as springs and spring communities.

(c) Require that results of bioregional assessments are integrated into the regulatory framework to support strategic catchment and water resource planning at regional scales, with associated caps to limit water take from each catchment or water resource, to ensure survival of water-dependent ecosystems and species. Project assessment criteria must be directly linked to these limits and plans to ensure that caps are not exceeded.

Conclusion

Australia's GAB springs are unique and of great ecological and cultural significance, and yet they are at risk under 'business as usual' environmental regulation which has been found to have limitations in several contexts. To increase the chances of survival of the remaining GAB springs, the recommendations provided here should be implemented and, over time, reviewed for their effectiveness in achieving the conservation of GAB springs and their groundwater-dependent ecosystems. While scientific effort is slowly building an understanding of GAB ecosystems, failure to strengthen the regulation of impacts on springs and their communities may mean that these efforts merely document the decline of springs and the extinction of species reliant on spring habitats and resources.

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Renee Rossini is an early career ecologist who focuses on the ecology of invertebrates, particularly species endemic to GAB springs, where she completed her PhD in 2018 on how the environmental requirements of endemic molluscs create and maintain their narrow patterns of distribution. She now works across Griffith University, The University of Queensland and the private not-for-profit Queensland Trust for Nature, engaging in spring ecology and conservation through policy, ecological and evolutionary research, and education partnerships.

Joshua Spring, Doongmabulla Springs complex, central Queensland. (Source: Ellie Smith, *Lock the Gate*; high resolution image obtained from Flinders University News, 12 June, https://news.flinders.edu.au/blog/2019/06/12/groundwater-plan-flawed-experts-warn/).

Doongmabulla Springs are a sacred site of the Wangan and Jagalingou People, where the *Mundunjudra* (Rainbow Serpent) travelled to shape the land, rivers and springs.

Improving Conservation Outcomes for Great Artesian Basin Springs in South Australia

Simon Lewis[1], and Colin Harris[2]

Abstract

It is estimated that there are more than six hundred springs and spring groups in the Great Artesian Basin (GAB), in Queensland, north-west New South Wales and South Australia. In the South Australian GAB, a limited number of important springs are protected within state reserves and through private initiatives and localised, targeted government programs. However, the vast majority of GAB springs in South Australia are unprotected on privately managed pastoral lands used for stock grazing. Communities of native species dependent on the GAB springs (an endangered ecological community under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act) are subject to uncontrolled and often severe ongoing impacts. Efforts at the national level to sustain GAB springs have focused primarily on reducing wastage from artesian bores to help maintain water pressure in the GAB. While this is very important, the impacts associated with land management practices are equally important and require a similar level of attention to find solutions which can also accommodate pastoral and other water users. This paper summarises the critical issues associated with conservation of GAB springs on pastoral lands in South Australia and proposes actions for future management. The main issue of concern is the impact of stock and pest animals on springs, and practical options for addressing those impacts. Exclusion of these animals is seen to be the key mechanism for protection of important GAB springs, and this usually means fencing. A GAB springs protection program is needed, and the paper explores a range of regulatory or governance options to support such a program. A preferred approach is a collaborative program involving state government agencies, pastoral lessees and others through application of management agreements under the South Australian *Native Vegetation Act 1991* or the SA *Natural Resources Management Act 2004*, supported by financial backing through the NRM Water Levy for the region. An effective compliance program is needed through collaborative arrangements between the state government and regional NRM Board. Recent research projects have developed criteria to be applied in determining priorities for GAB spring protection and remote monitoring techniques, although there are still some key gaps in the springs information base that need to be addressed.

Keywords: Great Artesian Basin springs, risk assessment, conservation and management, pastoral lands, governance framework

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Introduction

The Great Artesian Basin (GAB) is the largest groundwater basin in Australia and one of the largest in the world. It covers 22% of the Australian continent, including areas in Queensland, New South Wales (NSW), South Australia (SA) and the Northern Territory. The total volume of water stored in the basin is estimated at 64,900 million megalitres, with water in the GAB up to two million years old (SA Arid Lands NRM Board, 2010). Natural discharge from the GAB feeds a range of springs, mostly around the southern, western and

northern margins in South Australia, Queensland and New South Wales. Springs are formed where artesian pressure forces water to the surface. Most springs occur through fractures and faults along the margins of the basin, where confining beds are thin. There are other springs further into the GAB, such as Dalhousie Springs in the far north of South Australia, where water rises to the surface through geological fractures. Most of the springs have only small flows or seepages, but one at Dalhousie has a daily output of around 14 million litres per day (Harris, 1992). The eastern margin of the GAB abuts the Great Dividing Range, and it is from here that the majority of present-day recharge of the basin occurs (e.g. Habermehl, 2015).

GAB springs are often clustered, and researchers have applied a geographical classification system: small aggregates of springs form groups; aggregates of groups are spring complexes; and aggregates of complexes are spring supergroups. There are twelve supergroups across the GAB, seven in Queensland, two in NSW and three in SA (Lewis et al., 2013).

Within South Australia, the three supergroups (Dalhousie, Lake Eyre and Lake Frome) are classified as 22 spring complexes and 169 spring groups (Lewis et al., 2013). It is estimated that there are around 5000 spring vents. A spring vent is described as a single point of water discharge from the GAB, and in a large number of cases a spring comprises a single vent (e.g. Blanche Cup and the Bubbler in Wabma Kadarbu Mound Spring Conservation Park; Figure 1). In other cases, a spring comprises more than one immediately adjacent vent where the wetland vegetation has joined to form a single wetland area. Twelve Mile Spring, in the Lake Eyre spring supergroup, is a good example of this, with five vents.

Figure 1. Blanche Cup Spring, with extinct spring (Hamilton Hill) in background. In Wabma Kadarbu Mound Springs Conservation Park.

The GAB springs are of enormous cultural significance to Indigenous people, being their only reliable water source in the region for thousands of years. Numerous stories and song-lines are closely associated with the springs (Hercus & Sutton, 1985). The springs are also of great significance in a post-European settlement context. Early European explorers, such as John McDouall Stuart, relied heavily on the springs, and the establishment of the Overland Telegraph and original Ghan railway were inextricably linked with the GAB springs. Excellent examples of the links between mound springs and the Overland Telegraph can be seen at Strangways Springs and the Peake Telegraph sites (Harris, 1981).

The springs are of great ecological, evolutionary and biogeographical importance and support many endemic, rare and relict species of flora and fauna. The communities of native species which depend on the natural discharge of groundwater have been declared an endangered ecological community under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act).

It has long been recognised that there are two main threats to GAB springs:

- Pressure reduction in the GAB associated with the many thousands of bores sunk into the GAB.
- Disturbance of spring vegetation and geological features by stock and pest animals, weed invasion and, in some isolated cases, through excavation.

A limited number of important GAB springs are now protected. In Queensland, Edgbaston Reserve, managed by Bush Heritage Australia, is an excellent example of a private initiative to protect GAB springs, while Elizabeth Springs are protected with a government reserve, Elizabeth Springs Regional Park. In South Australia, a variety of programs have been implemented to safeguard GAB springs against the effects of grazing by stock and pest animals, and to provide protection against other forms of disturbance:

- Protection in public conservation reserves (Witjira National Park, Wabma Kadarbu Mound Springs Conservation Park and Kati Thanda-Lake Eyre National Park).
- Weed control (particularly palms) at Dalhousie Springs (Witjira).
- Protective fencing established by pastoral lessees (e.g., Strangways Springs, fenced by former Anna Creek lessees S. Kidman & Co; springs on Billa Kalina).
- Protective fencing, established by the then South Australian Department of Environment and Planning in the 1980s, at 10 individual springs on pastoral leases.
- De-stocking of Finniss Springs Station following transfer to the Arabana Traditional Owners.
- De-stocking of part of Stuart Creek pastoral lease, including several GAB springs, near Lake Eyre South, by BHP as an environmental offset for native vegetation clearance undertaken elsewhere (Figure 2).

While these activities have resulted in important conservation outcomes, the vast majority of GAB springs in South Australia are on pastoral lease land subject to stock grazing. This paper focuses on strategies that could improve the conservation status of these pastoral land springs while also taking into account the land and stock management requirements of pastoral lessees.

Conservation of GAB Springs on Pastoral Lease Land in South Australia

The distribution of springs and spring groups in northern South Australia is illustrated in Figure 3. Seventeen of the 22 spring complexes in South Australia are on pastoral leasehold land. As noted previously, some springs on pastoral land have been protected from grazing impacts, but the vast majority remain subject to uncontrolled and often severe impacts by stock (mainly cattle) and pest animals (Lewis, 2001).

Comprehensive studies commissioned by the state environment agency in the 1980s (SA Department of Environment and Planning, 1986) concluded that the following spring groups were of particular conservation significance: Hawker, Freeling, Billa Kalina, Lake Callabonna and Public House Springs, and Francis Swamp. All of these spring groups are on pastoral leases and, apart from three of the Billa Kalina springs, are open to stock and pest animals.

Figure 2. McLachlan Spring on Stuart Creek Pastoral Lease, included in an area de-stocked as part of an environmental offset for native vegetation clearance approved elsewhere.

Risk Assessment for GAB Springs on Pastoral Lands

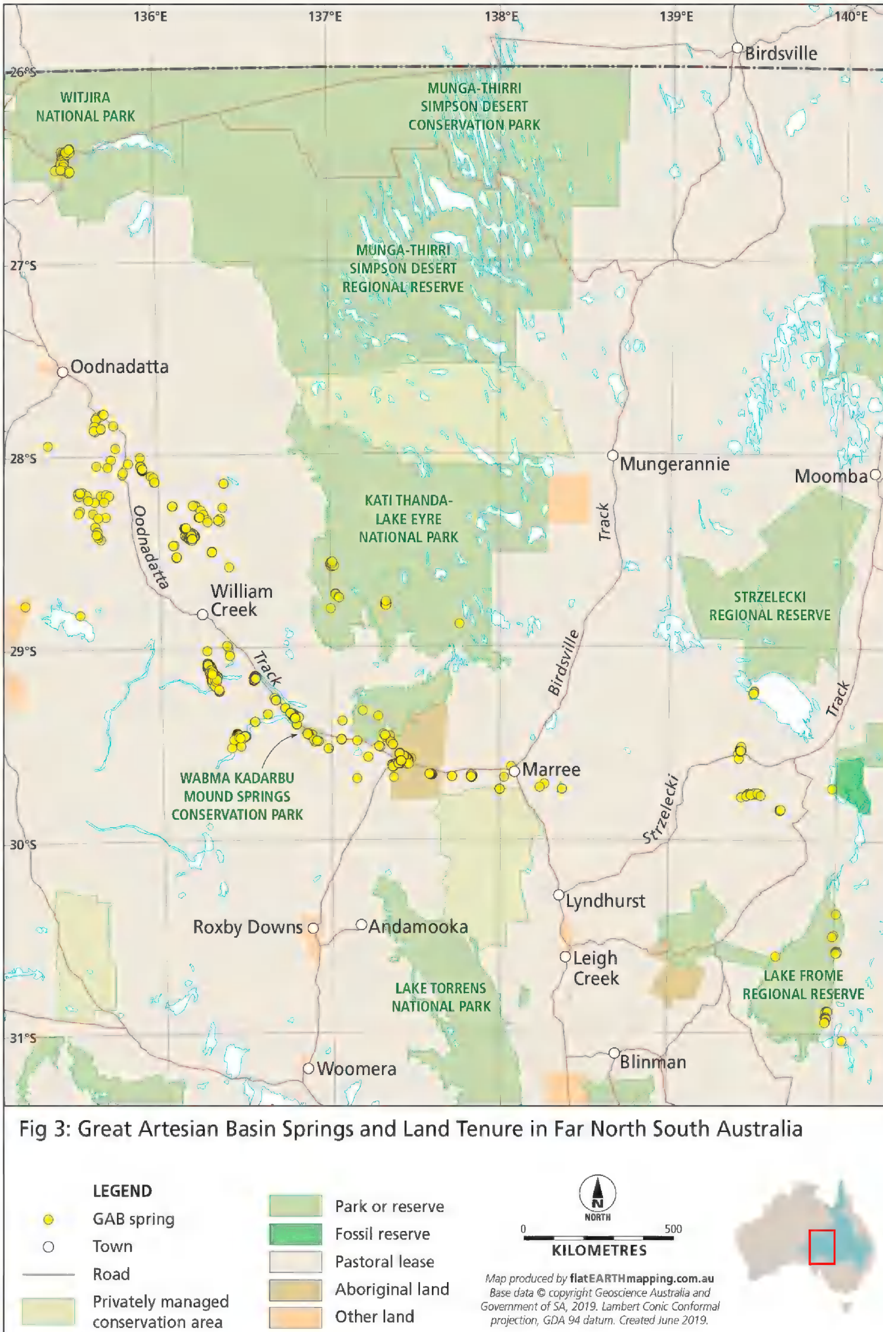
The greatest risk or threat for all GAB springs is a reduction in water pressure leading to reduced flows in springs, with consequent impacts upon spring biota and possibly geomorphological structures. More than 4700 artesian bores have been established across the whole GAB. While many bores have been capped and controlled, there are still many with uncontrolled flows. It is estimated that natural flows from GAB springs have declined by up to 40%, and many springs have dried up, largely as a result of extraction via artesian bores (Green et al., 2013; Fairfax & Fensham, 2002). The loss of springs in Queensland as a result of aquifer drawdown has been most severe in the Flinders River, Bourke, Springvale, Barcaldine and Eulo supergroups. In South Australia, many of the more elevated springs have ceased to flow as a result of pressure reduction (Fairfax & Fensham, 2002).

The pressure reduction situation has been addressed, in part, through programs at the state and national levels to rehabilitate and control artesian bores to minimise wastage of GAB water. The GAB Sustainability Initiative (GABSI) has been a good example of such a program, while earlier control programs in South Australia date back to the late 1970s. In addition, the portion of the GAB within South Australia has been declared a Prescribed Watercourse (Far North Wells Prescribed Area), providing a mechanism for protective measures through the Water Allocation Planning process. Maintaining or improving water pressure in the GAB is not a focus for this paper. Instead, this paper focuses on the particular risks for GAB springs associated with physical and chemical disturbance of springs, particularly through land management practices.

Impacts of Stock and Pest Animals

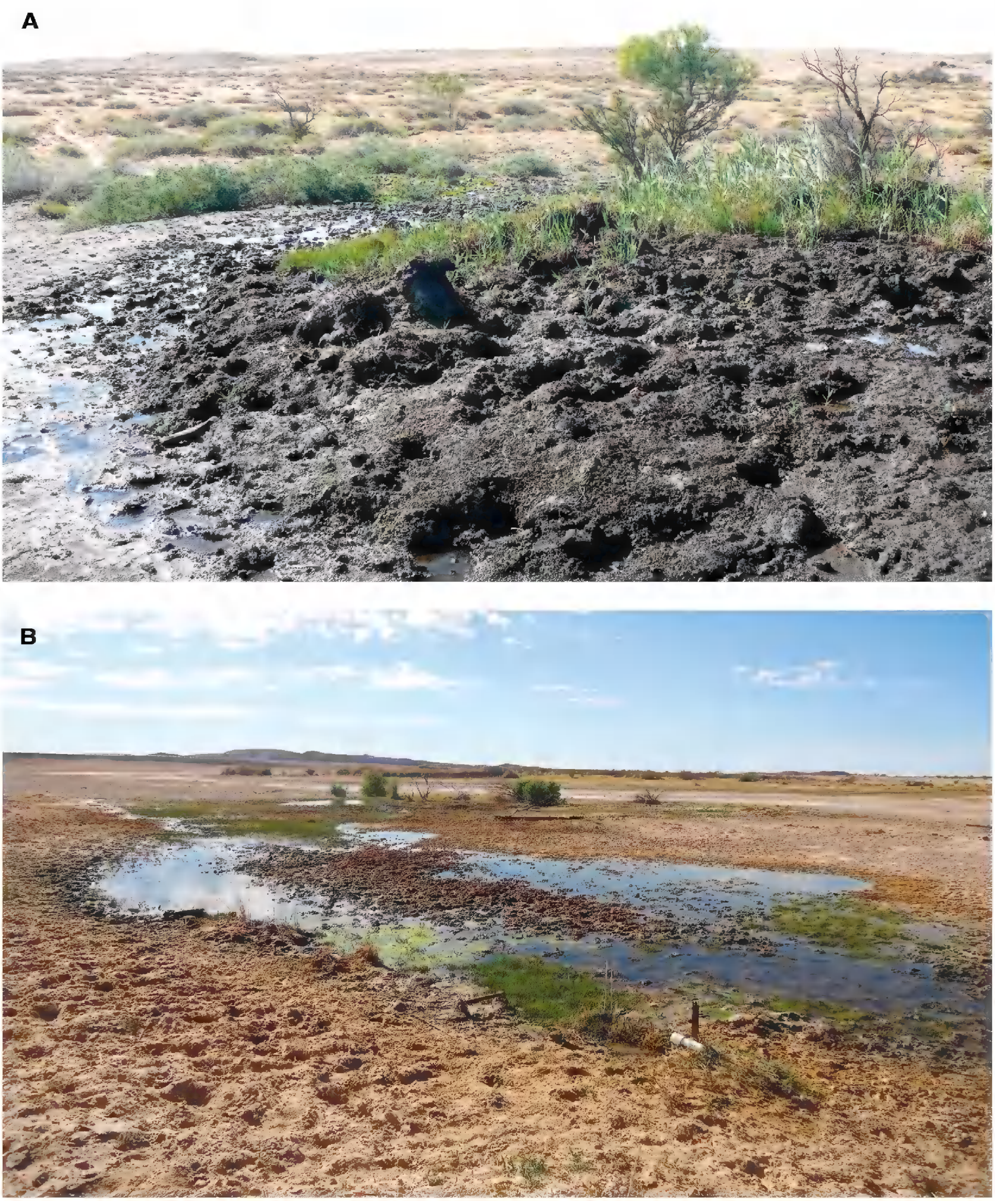
Stock and pest animals have a direct impact on spring vegetation and can lead to the loss of plant species, as well as pugging and elevated nutrient concentrations (principally nitrates and phosphates) in spring waters and sediments (Green et al., 2013). There are concerns that spring fauna, including invertebrates and potentially fish, may be seriously affected, and there is evidence that there have been losses of endemic flora and fauna (Fatchen & Fatchen, 1993; Kovac & Mackay, 2009).

Figure 3. Great Artesian Basin Springs and Land Tenure in Far North South Australia.



Weed species can be introduced by stock and feral animals, and weed growth can be promoted by the elevated nutrient levels. Grazing animals can also disturb or destroy geomorphological structures associated with the springs, as illustrated in Figure 4. Cattle are the predominant livestock in springs country in South Australia, while pest animals include horses, donkeys, camels and rabbits.

Figure 4. Springs showing cattle damage (A), and impact of horses (B).



The above observations are based upon work undertaken over the last 40 years or so by GAB spring researchers, government monitoring personnel, volunteers and others. While the evidence is convincing, there is scope for further research into aspects such as the impact of grazing, pugging, pollution, etc., on spring invertebrates (including the high number of endemic species), and the impact of introduced grazing animals on nutrient levels in spring waters and sediments.

Weeds

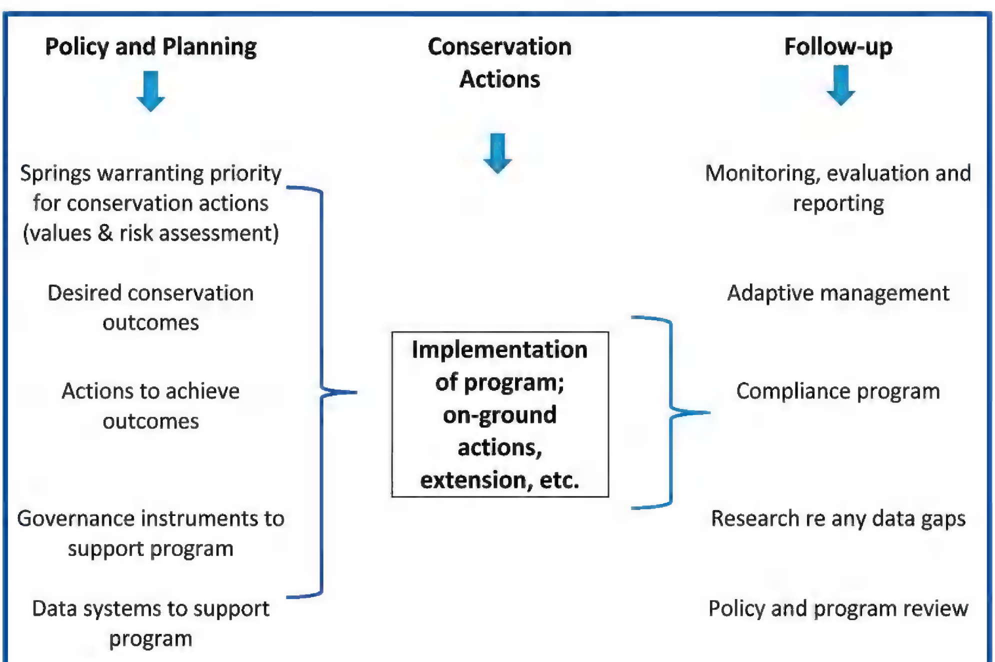
Weeds have been introduced to GAB springs through a range of mechanisms. Some introduced plants were deliberately planted in the springs environs – such as date palms (*Phoenix dactylifera*) at Dalhousie and other springs such as Nilpinna and Big Perry. Other weed species have been brought in by stock, pest animals, or on the clothing or vehicles of visitors. Apart from palms, other weeds in springs include the alien grass *Polypogon monspeliensis*, and species introduced from other parts of Australia, such as the grass *Bambusa* sp. (bamboo) and the forb *Spergularia marina*. Weeds can out-compete native vegetation and have impacts upon spring flora and fauna. Some weeds, such as palms and bamboo, can also use large volumes of spring water, thus affecting spring flows (Green et al., 2013).

The overall knowledge base regarding weeds in GAB springs is by no means complete, although some information is available regarding weeds in GAB springs within reserves and other springs where monitoring has been undertaken. Most springs in South Australia are poorly documented in terms of present-day weed issues and more information is needed.

Setting Objectives for GAB Springs Conservation on Pastoral Lands

Australia's record in protecting its internationally significant GAB springs is very poor and an improved framework is needed, clearly setting out, amongst other things, objectives, actions to achieve those objectives, and a regulatory program to underpin the whole framework. A conceptual framework for this is provided in Figure 5.

Figure 5. Conceptual framework for conservation of GAB springs on pastoral lands.



The data systems needed to support an effective conservation framework are not discussed in detail here. However, we recommend the collection of baseline data on the characteristics and condition of springs, and monitoring systems to determine changes over time and the effectiveness of conservation actions. Data systems such as these are essential but beyond the intended scope of this paper.

Desired Outcomes

In terms of biodiversity conservation, the recent Commonwealth-funded Desert Jewels project (see Gotch, 2013) sets, as a general desired outcome for GAB springs, *maximum natural biodiversity*, which can be interpreted as:

- springs with the full suite of native flora and fauna expected to occur;
- spring flows sufficient to maintain biodiversity; and
- natural ecological processes occurring without disturbance.

As noted in the Introduction, many springs contain native species of particular conservation significance. Where these occur, their conservation should be highlighted as a specific desired outcome. Achievement of the above "maximum biodiversity" outcome should also cover the needs of species of particular conservation significance, but this may not apply in all cases. The geomorphological structures and features of GAB springs also need to be highlighted. With these factors in mind, the desired outcome in terms of biodiversity conservation can be expressed as follows:

- Springs functioning with maximum diversity of native flora and fauna present, with species of particular significance conserved, geomorphological features protected, and with natural ecological processes occurring.

Many springs on pastoral lands have been used as water-points for stock for up to 150 years. De-stocking entire spring groups without supplementary actions might therefore create difficulties for stock management. Taking this into account, another desired outcome is:

- Rationalising stock access to water in areas where springs have historically been an integral stock-watering resource in property management.

On-ground Actions to Achieve Desired Outcomes

At the property management level, the following actions would contribute to the above desired biodiversity conservation outcomes:

- Maintaining capping and control over existing artesian bores, as a contribution to the broader GAB pressure management program.
- Maintaining strict control over the installation of any new artesian bores or other water extraction activities that might contribute to draw-down at nearby springs.
- Exclusion of stock and pest animals from spring wetland areas.
- Control of weeds.

Given the land management focus of this paper, comment on the last two of these points is provided below.

Stock and Pest Animal Exclusion

Healthy GAB springs require cessation of uncontrolled access by stock and pest animals. Two general approaches can be considered.

The first is reservation for conservation purposes, either as public conservation areas through state national parks and wildlife legislation, or through private conservation initiatives. In Queensland, Edgbaston Reserve, managed by Bush Heritage Australia, is an excellent example of important GAB springs being protected through a private conservation initiative. In South Australia, while not involving GAB springs, Witchelina Nature Reserve (Nature Foundation SA) and Bon Bon Reserve (Bush Heritage Australia) are good examples of former pastoral properties being purchased for conservation purposes. Reservation of additional spring areas under state legislation is theoretically possible but, at least in South Australia, seems unlikely in the current resources and political climate. None of the above addresses the problem of pest animals, *per se*, but it does set the scene for conservation actions including pest animal control.

The second option for stock and feral animal exclusion on pastoral lands is protection of selected spring areas while retaining them under pastoral

leasehold tenure. This could involve taking entire pastoral paddocks out of production but is more likely to involve fencing of selected springs or spring groups. Bearing in mind fencing programs undertaken on pastoral areas in the past 30 to 40 years, the following relevant observations can be made:

- Fencing individual springs is generally not a preferred option, particularly if the fencing is tight around the spring with the wetland tail extending through the fence. It is a small conservation return for effort and leaves fencing vulnerable to pressure from stock.
- Fencing of groups of springs is far preferable, with fencing well removed from spring wetland areas. However, fencing of groups of springs is likely to incur high initial capital costs and needs a clear commitment to the costs and effort associated with monitoring and maintenance.
- If there is an individual spring, not part of a group, that warrants protection, the fencing should be well removed from spring wetland areas and should encompass, if possible, the entire spring tail.
- Fencing, particularly in remote areas, is expensive – estimated at up to $5,000/km (B. Arnold, pers. comm.). Maintenance of fencing can also be relatively expensive and clearly requires ongoing commitment.
- In terms of pastoral manager participation, a small number of pastoral lessees have actively supported and contributed to the protection of GAB springs from stock and feral animal impacts. Other pastoral lessees have declined to be actively involved but have been willing to allow outside parties to erect and maintain fencing. Accordingly, it can be concluded that some spring fencing programs will need to be managed by a party other than the pastoral lessees, or will need to link with sufficient incentives to encourage lessee involvement, or will need to be a statutory requirement.

The fencing of Strangways Springs on Anna Creek pastoral lease in the 1990s by then lessees S. Kidman & Co is an excellent example of a successful fencing program undertaken as a private initiative. Approximately 80 active springs (and many extinct springs) have been fenced. However, this fenced area has no particular conservation status and there is no management agreement or covenant providing long-term security. As noted above, pastoral management needs in terms of stock water also need to be taken into account. In some areas, pastoralists have relied on springs for stock watering. However, as also noted above, there are many situations where stock have had an impact on groups of springs whereas just one or possibly two water-points would suffice. Restricting water-points in a particular area can also have benefits for stock management, particularly in terms of mustering (A. Williams, pers. comm.).

Where springs have a history of being used for stock watering, the following options for fencing of GAB springs are proposed:

- Where fencing of a group of springs is proposed, it may be possible to exclude one or two of the outer springs, to be used for stock watering.
- Where an entire group is to be fenced, it may be possible to pipe water from one of the outer springs to an external trough/water-point.
- If an individual spring that has been an important water-point is to be fenced, piping water to an external water-point may be an option.

It is worth noting that very early pastoralists often fenced springs and piped water to an external trough with a two-fold purpose: to prevent stock pugging and polluting the main water source (and potentially becoming bogged) and to maintain a clean water supply. This generally occurred before the advent of artesian bores, when the springs comprised virtually the only stock water resource.

Pulse grazing of areas/paddocks that include GAB springs has also been cited as a management option that may have conservation benefits. This could involve letting cattle into springs paddocks in wet seasons when free water is widely available – meaning less stock pressure on springs – but excluding stock in dry seasons when they would otherwise put pressure on springs. However, more information about the impacts and practicalities of this option is needed before any conclusions can be reached about this as a legitimate conservation practice.

Another factor noted at a number of GAB springs fenced for conservation purposes is the proliferation of reeds (particularly *Phragmites australis*). The proliferation of *Phragmites*, a local native species, is regarded by some as a conservation threat to the GAB springs through competition and habitat change (e.g. Davies et al., 2001; Kodric-Browne et al., 2007). This is not explored further in this paper, other than to note that additional information is needed about the merits of active management of *Phragmites* in this situation.

Control of Weeds

The control of weeds requires a spring by spring approach or a spring group by spring group approach. Weed infestations are generally not severe in springs in the Lake Eyre or Lake Frome supergroups, whereas palms have been a significant issue at Dalhousie and have been subject to extensive control programs. In the Lake Eyre supergroup there are isolated instances of bamboo (*Bambusa* sp.) (e.g. Nilpinna, Birra Birriana Springs) (Lewis, 2001).

Providing a Regulatory or Governance Framework for On-ground Actions

The current regulatory framework relating to GAB springs provides no effective protection for springs on grazing lands and is heavily dependent upon voluntary arrangements being developed with individual land managers. As noted above, the communities of native species associated with GAB springs have been declared an endangered ecological community under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act). While this reflects the importance of GAB spring communities, it is essentially a reactive mechanism giving the relevant Commonwealth Minister certain powers in the event of actions or proposed actions that could impact upon spring biota.

At the state (South Australian) level, the *Pastoral Land Management and Conservation Act 1989* and *Natural Resources Management Act 2004* set a general duty of care for land management in the pastoral zone. For example, the Pastoral Act requires pastoral lessees to:

- prevent degradation of the land; and
- endeavour, within the limits of financial resources, to improve the condition of the land.

Similarly, the Natural Resources Management Act "seeks to protect biological diversity and, insofar as is reasonably practicable, to support and encourage the restoration or rehabilitation of ecological systems and processes that have been lost or degraded".

While the intent of these provisions accords with conservation objectives, they are essentially aspirational statements that have had no clear effect in terms of maintaining GAB springs in good condition. More specific regulatory or other governance provisions relating to GAB spring conservation of pastoral leases are described below.

Management of Water Extraction from the GAB for Pastoral Use

As already noted, it is not the intent of this paper to address the many factors involved in the reduction of water pressure in the GAB. However, from a pastoral management perspective it is relevant to note that the GAB in South Australia is a prescribed water resource under the *Natural Resources Management Act 2004* and is subject to a Water Allocation Plan (WAP) prepared in 2009. One of the key objectives adopted under the 2009 WAP is to protect environmental assets, such as the groundwater-dependent spring ecosystems. To that end, the WAP includes the following criteria:

- There shall be no new wells for the purpose of the taking of water within 5 km of any springs.
- The taking of water shall not result in any unacceptable drop in pressure in the vicinity of springs due to the taking of water.
- A decline in pressure in the vicinity of springs may be acceptable if the proponent can demonstrate that any drop in pressure will not have any unacceptable impact on the spring ecology.
- The potential of a pressure drop due to the taking of water would trigger the requirement for a proponent to prepare an Environmental Impact Report (EIR) which will result in appropriate management conditions relevant to the level of potential environmental impact.

While the first of the above is very prescriptive, the others are somewhat problematic given the complexity of the systems and the natural fluctuations in spring flows.

The Water Allocation Plan goes on to acknowledge the need to protect GAB springs from surface impacts. The WAP notes:

> There is also a need to ensure that the GAB springs are protected against pollution, erosion and habitat destruction as a result of activities such as grazing, destroying of vegetation and excavation or removal of sediments at or in the immediate vicinity of the springs.

This provision has not been applied in any meaningful way: as illustrated in Figure 6, severe grazing impacts are common on GAB springs on pastoral lands. The WAP is currently under review. While the revised version may be able to address stock/feral animal impacts more directly, there may be other mechanisms more suited to the protection of springs or spring groups from grazing impacts and these are discussed below.

Mechanisms to Support Conservation of GAB Springs on Pastoral Lands

This paper has noted some progress in protection of GAB springs on pastoral lands over the last 35 years, almost exclusively achieved through voluntary arrangements with pastoral lessees. However, the vast majority of GAB springs in South Australia remain open to grazing impacts, and it is telling that these include all but three springs in the hundreds of springs in the six spring groups rated as of particular conservation significance in surveys in the 1980s (SADEP, 1986).

Mechanisms to support GAB springs conservation on pastoral or other lands used for production are largely a state responsibility and, accordingly, vary from one state jurisdiction to another. Within South Australia, the following are relevant, although only in one instance have any of them been applied for GAB spring conservation.

Reference Areas under the Pastoral Land Management and Conservation Act 1989

Through the *Pastoral Land Management and Conservation Act 1989*, the Pastoral Board may declare a specified area of pastoral land to be a reference area for the purposes of evaluating the effect that the grazing of stock has on the land. A reference area cannot exceed one square kilometre in size and will, where necessary, be fenced by the Minister. A lessee is not obliged to maintain a reference area or its fences unless there is a particular agreement to the contrary with the Minister. Stock are not permitted in a fenced reference area. There is no direct compensation to the lessee, but any reduction in value of the lease is taken into account when the lease is next revalued.

This mechanism is theoretically applicable to protection of GAB springs but is by no means tailor-made for the purpose. The one square kilometre criterion could be a limiting factor with some spring groups, and there are limited options for providing assistance and incentives for the land managers.

Heritage Agreements under the Native Vegetation Act 1991

The Heritage Agreement Scheme for protection of native vegetation was introduced in 1980, and there are now over 2800 Heritage Agreements covering approximately one million hectares, mostly in the agricultural regions of the state. The Scheme currently operates under the *Native Vegetation Act 1991*. In brief, a Heritage Agreement is a binding conservation agreement between the responsible Minister and a landholder for the protection of a specified area of native vegetation. The Agreement attaches to the land title and therefore continues to apply with any change in land ownership. Importantly, an Agreement can include assistance with fencing and other aspects of management. It can also include other financial incentives for the landholder. Some lateral thinking may be required, however, as incentives used under this scheme in southern agricultural areas may not be readily applicable to pastoral areas. Nevertheless, there are several examples of Heritage Agreements established in the Far North of South Australia.

Thus, a Heritage Agreement could apply to an area including one or more GAB springs and could include incentives such as fencing and management assistance. In many respects it is a very suitable, flexible mechanism for protection of GAB springs. However, current legal advice (R. Seaman, SA Department for Environment and Water, pers. comm.) is that there are legal difficulties in establishing Heritage Agreements over areas under pastoral lease which need to be resolved.

Figure 6. One of several springs at Levi Springs, in good condition (A); and more recently (B), showing recent grazing impacts.

Management Agreements under the Natural Resources Management Act 2004

Section 205 of the *Natural Resources Management Act 2004* allows for management agreements to be established for "the protection, conservation, management, enhancement, restoration or rehabilitation of any natural resources". This is a very flexible mechanism for a management agreement between a landholder and the relevant Minister, and can include incentives provided by the Minister.

Native Vegetation Offsets: the Significant Environmental Benefits Program

Under the *Native Vegetation Act 1991*, landholders who receive permission to clear native vegetation are required to offset the effects of that clearance through other actions to achieve a net environmental benefit, known as a Significant Environmental Benefit (SEB). The SEB can be achieved through other conservation measures on the landholder's property, through agreed measures on a third party's property, or through payment into the Native Vegetation Fund. Such payments into the Native Vegetation Fund are then made available through SEB grants to fund native vegetation conservation projects.

This creates two potential avenues for funding of GAB spring protection programs:

- Protection works by a third party as an SEB offset for clearance of native vegetation undertaken elsewhere. For example, a mining company undertaking approved vegetation clearance in the region might finance the protection work as an SEB offset. The SA Department for Environment and Water's website sets out the following potential process which might well be applicable to a group of GAB springs on pastoral land:
  - A pastoral land manager can nominate a GAB springs area as a proposed SEB offset site and can include costings for fencing and fence maintenance over a period of, say, 10 years.
  - The area is then recorded on a register of potential offset sites.
  - A third party, such as a mining company, with a need to provide an SEB offset linked with an approval by the Native Vegetation Council to clear native vegetation elsewhere, could then select the GAB springs site and provide the funds for protective fencing and ongoing maintenance for a specified period.
- The second potential option is for a pastoral land manager to seek funding through the SEB grants program to undertake the protective works directly.

This mechanism could be useful and could be combined with the establishment of Heritage Agreements or NRM management agreements. The first of the above options could be particularly useful where a pastoral land manager is willing to have a group of springs protected but is not willing to have an active involvement in the protective works. Its main drawback is that it is essentially an opportunistic program that, in effect, relies on ongoing clearance of native vegetation to generate continued SEB offset requirements. There is already one example of this mechanism in practice in mound springs country. A portion of Stuart Creek pastoral lease near Lake Eyre South has been de-stocked by the lessee (BHP) as an offset for native vegetation clearance elsewhere. This area includes GAB springs such as Gosse and McLachlan Springs.

Water Levies under the Natural Resources Management Act 2004

As part of the agreement under the National Water Initiative, the *Natural Resources Management (NRM) Act 2004* provides for an NRM water levy to support the development and management of water resources. In the Far North Wells Prescribed Area a levy is raised from industrial water users as well as from co-produced water extracted by the petroleum industry.

The Business and Operational Plan 2017/18 – 2019/20 for the SA Arid Lands NRM region (Volume 2 of the Regional NRM Plan) identified income of $1.715 million from the NRM Water Levy in 2018–2019. The same plan foreshadowed expenditure of around $600,000 on water-related programs during the same year – just over one-third of the levy income.

The processes associated with water levies for the Far North Wells Prescribed Area do not directly include any mechanisms relating to protection of

groundwater-dependent ecosystems such as GAB springs. However, the NRM Act does include a strong emphasis on the need to protect natural ecosystems that depend upon water resources, and it is recommended that a portion of water levy funds be allocated to the protection of GAB springs. This could potentially link with the establishment of protective mechanisms such as Heritage Agreements or NRM management agreements (see above).

Combining Governance Mechanisms

As described above, South Australia has a range of regulatory or governance mechanisms that could be effective in supporting the conservation of GAB springs on pastoral lands. However, with the single exception of an SEB offset agreement with BHP on the Stuart Creek pastoral lease, these mechanisms have not been applied. A greater commitment of will and resources is needed, led by governing bodies (Commonwealth, state and regional) in collaboration with land managers and appropriate non-government organisations. There is the potential for a mix of governance mechanisms to be applied for the protection of GAB springs on pastoral lands. The native vegetation SEB offsets program is an attractive option, particularly given the level of mining activity currently occurring in Far North SA. Likewise, there is considered to be a strong case for increased Water Levy funding being allocated towards spring protection. Mechanisms such as Heritage Agreements or NRM management agreements could provide a lasting mechanism to maintain protection effectively in perpetuity.

A major commitment is needed to a joint program involving pastoral lessees, the SA Native Vegetation Council and the SA Arid Lands Natural Resources Management Board (or its successor). There is also scope for involvement by conservation-based non-government organisations and major 'developers' in the region, such as mining companies.

Determining Priorities for Protection of GAB Springs

A recommended approach for assessing the ecological values of GAB springs and spring groups is provided by Green et al. (2013). Five key criteria are described as:

- Diversity – of species or habitats and/or hydrological and/or geomorphological processes.
- Distinctiveness – e.g. rare or threatened species or communities or rare geomorphological features or processes.
- Vital habitat – for unusually large numbers of species of particular interest, or species of interest in critical life cycle stages.
- Evolutionary history – demonstrating features or processes of particular interest in the development and evolution of Australia's biota or landscapes.
- Naturalness – springs not adversely affected by human activity to a significant level.

A further relevant criterion is *resilience*. Monitoring over many years has shown that springs subject to severe stock/pest animal pressure often recover very well – at least vegetatively – when that pressure is removed. The recovery of spring fauna, particularly invertebrates, is less well understood. The extent of pugging and contamination in springs accessed by cattle and pest animals raises serious concerns about impacts on spring invertebrates, and more research on this topic is needed.

Vulnerability is another factor to be considered. A good example of this is large groups of springs such as Hawker Springs. Observational evidence suggests that the outermost springs in a large group are more vulnerable to disturbance by stock and/or feral animals than springs towards the centre of the group – a reverse piosphere effect. However, this has yet to be investigated with scientific rigour.

Additional Information Needed to Conserve and Manage Springs

There are many aspects of the conservation and management of GAB springs that would benefit from additional information. However, in terms of improved outcomes for GAB springs on pastoral lands there is a more limited range of topics that warrant priority:

- Establishment of a more comprehensive and accessible database regarding springs and their condition, including the status of any weeds.
- More information about the effects of stock and pest animals on spring biota, particularly invertebrates, and on nutrient

levels (including trends when springs are de-stocked).

- More information about the impact of stock and pest animals on larger groups of springs, and the possible occurrence of a reverse piosphere effect.
- More information about the merits, impacts and practicalities of pulse grazing of spring areas.
- More information about the management of reeds (*Phragmites* sp.) that have proliferated in several GAB springs following stock exclusion.

Conclusions and Recommendations

South Australia has a rich array of GAB springs, occurring as 22 spring complexes. While many springs of national importance are protected within reserves and other conservation zones, the vast majority of spring complexes occur on pastoral lands that are mainly used for cattle production. Seventeen of the spring complexes in SA are on pastoral lands and are subject to significant impacts by stock and pest animals in terms of vegetation destruction, pugging and pollution. A small number of notable exceptions occur where high-value GAB springs have been protected by pastoral lessees and by the state environment agency. Given the international importance of GAB springs, their current status in terms of protection and management is quite unsatisfactory and urgent action is required.

This paper recommends that the desired management target for GAB springs should be:

- Springs functioning with the maximum diversity of native flora and fauna present, with species of particular significance conserved, geomorphological features protected, and with natural ecological processes occurring.

The main practical option for restricting or preventing surface impacts at springs is exclusion of stock and pest animals. This could occur by taking existing paddocks out of production or by more localised, targeted fencing. There is potential for a mix of existing governance mechanisms to be applied for the protection of GAB springs on pastoral lands in South Australia.

- The native vegetation SEB offsets program is an attractive option, particularly as it provides for third parties to be involved in funding protective works and ongoing maintenance for spring groups on pastoral lands.
- Land management agreements such as Heritage Agreements under the Native Vegetation Act or management agreements under the Natural Resources Management Act could provide a lasting mechanism to maintain protection effectively in perpetuity.

In summary, suitable protective mechanisms are available for protection of GAB springs on pastoral lands but have not been applied to a satisfactory extent because of a lack of commitment and resourcing. A GAB springs conservation program is needed and the preferred option is a program involving pastoral lessees, traditional Indigenous owners, the SA Native Vegetation Council and the SA Arid Lands Natural Resources Management Board (or its successor) – with potential input also from conservation-based non-government organisations and major ‘developers’ in the region, such as mining companies. As part of this, there is a strong case for increased Water Levy funding being allocated to GAB springs protection and management.

This governance framework for South Australia will not be directly transferable to other states with GAB springs, but a number of important elements can be identified:

- A robust database and a clear process for identifying springs or spring groups that warrant priority for conservation.
- An incentives program for landholders, including the initial protection works and ongoing maintenance of those protective measures (an offsets program with scope for third-party involvement seems particularly suitable).
- A regulatory framework that underpins the incentives program, manages monitoring and compliance, and also provides security for the protective measures by means of a covenant or similar mechanism.

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Author Profiles

Simon Lewis is a retired South Australian public servant, having spent most of his 34-year career in the state Environment Department. He first travelled to the GAB springs in 1977 and, from the early 1980s, was involved in the Department's spring fencing program which is referred to in this paper. He is a foundation member of Friends of Mound Springs, established in 2006, and is the long-standing Secretary of that group.

Colin Harris PSM is a retired South Australian public servant who spent over 30 years of his career in the state Environment Department. He has been actively involvement in the conservation and management of mound springs since the early 1970s, and for this, and other conservation work, he was awarded the Public Service Medal in 1999. He is the foundation President of the Friends of Mound Springs and continues to the present in that role.

Development of an Adaptive Management Plan and Template for Sustainable Management of Great Artesian Basin Springs

Anne E. Jensen[1], Simon A. Lewis[2], and Megan M. Lewis[3]

Abstract

Great Artesian Basin (GAB) springs are unique environmental assets of international ecological, hydrogeological and cultural value, and water assets of immense economic and social significance to communities, mining and pastoralism in the arid and semi-arid regions of the GAB. Human use of GAB water has introduced threatening processes that risk compromising these important spring values. The threats include reduced spring outflows due to loss of artesian pressure and surface disturbances around spring vents and groundwater-dependent wetlands.

To address these threatening processes, the GAB Adaptive Management Plan and Template have been developed using evidence-based methodologies to identify, assess and manage risks to spring groups across the GAB. The GAB Springs Adaptive Management Plan aims to ensure maintenance of artesian pressures that sustain spring flows and encourages sensitive land-use practices in and around springs to protect spring geology and ecology, while minimising disruption to current users of basin water resources. Implementation of the Adaptive Management Template requires a robust, comprehensive and interactive basin-wide database which combines all available information on spring characteristics, condition, trends, values, groundwater-dependent ecosystems, risk factors and their impacts. An objective, rigorous and cost-effective basin-wide monitoring program linked to the database will be essential to assess the condition of assets and the effectiveness of management actions. The GAB Adaptive Management Plan and Template bring together relevant evidence from recent research to provide a decision framework for assessing the risks to springs and determining appropriate management actions to address those risks. It is recommended that the Plan and Template be adopted as an endorsed implementation strategy as part of the Implementation Plan for the updated National GAB Strategic Management Plan (2018–2033).

Keywords: Great Artesian Basin, adaptive management, spring values, threats, evidence-based methodologies, risk assessment, artesian pressure, land-use practices

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Introduction

Great Artesian Basin (GAB) springs are unique environmental assets of international ecological, hydrogeological and cultural value, as well as being water assets of immense economic and social value to communities, mining and pastoralism in the arid and semi-arid regions of the GAB. Consumptive use of GAB water is estimated to return about $13 billion of production annually, including $4 billion in stock, $6 billion in mining, $2 billion in gas and $1 billion from tourism (GABCC, 2018).

Human use of GAB water has introduced threatening processes that risk compromising important spring values, from reduced spring outflows due to loss of artesian pressure and surface disturbances around spring vents and wetlands. The vast majority of GAB springs are on lands managed for stock production or other agricultural activity.

Various programs since the 1970s have addressed the primary issue of reducing artesian pressure, working to cap and control flows from otherwise uncontrolled bores. These included state-based programs and the national GAB Sustainability Initiative (GABSI) to rehabilitate flowing bores and convert open bore drains to piped systems (Brake, 2020). While these programs have achieved significant success, when the most recent GAB Sustainable Management Plan was being prepared in 2018, approximately 40% of bores and 18% of open bore drains still needed to be replaced by closed delivery systems (GABCC, 2018). Updated figures suggest that 33% of bores and 13% of bore drains still remain to be controlled in 2020 (Brake, 2020). If this work can be completed, a further 116,261 ML/year of uncontrolled flows from GAB sources could be saved.

The second main threat to artesian springs, surface disturbance, has received less coordinated attention (Brake et al., 2020). The threats include physical excavation of spring vents, impacts of stock grazing on native vegetation, increased nutrient loads from stock manure, pugging damage to pools and aquatic habitats affecting spring fauna, invasive weeds and visitor impacts.

Figure 1. The Great Artesian Basin, indicating the location of 13 spring supergroups and the directions of groundwater flow in the basin (Figure constructed by M. Keppel from data sourced from Ransley et al., 2015).

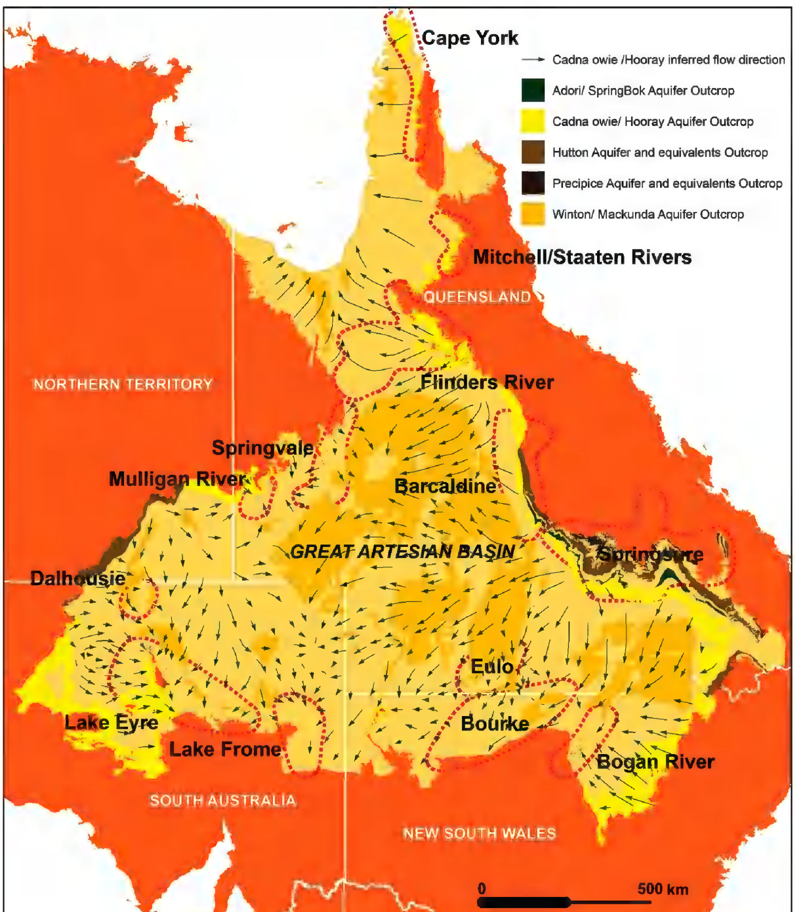

Figure 2. Fretted travertine rims are a recognised topographic structure seen at a number of outlets at Strangways Springs in the Lake Eyre supergroup (Photo: C. Harris).

Scientific knowledge of the basin resource and its connectivity to other surface and groundwater systems has significantly increased since the 1980s, leading to the Geoscience Australia *Hydrogeological Atlas of the Great Artesian Basin* and the GAB Water Resource Assessment (Habermehl, 1982; Habermehl & Lau, 1997; Ransley et al., 2015). In the South Australian section of the GAB, more than $14 million has been invested since 2010 in research projects into the physical, hydrological and biological characteristics and processes of mound springs, providing improved knowledge to inform future decision making and management for GAB springs (National Water Commission, 2013; DEWNR, 2016). Springs in the Queensland GAB were described and assessed in 2016 for potential impacts from mining developments, with information on physical characteristics, biological values and water chemistry recorded in a database (Fensham et al., 2016). Very high rates of spring loss were recorded across the Queensland supergroups of GAB springs.

During 2019 and early 2020, a South Australia-based project team developed an adaptive management plan and template as a pro forma for an evidence-based, coordinated approach to the conservation and management of GAB springs (Brake et al., 2020). This project, funded by the Australian Government and jurisdictions encompassing the GAB via the Great Artesian Basin Coordinating Committee (GABCC), is relevant to springs across the GAB and its core elements are described in this paper.

Spring Values

Artesian springs in the GAB are features of iconic geological, evolutionary, ecological and biogeographical significance. They have been features in the landscape across the basin for many thousands of years. The GAB springs are of enormous cultural significance to Indigenous people, being their only reliable water source in most of the region prior to European colonisation. Archaeology in and around spring sites reflects the importance of these

permanent water sources in the otherwise dry landscapes. Many springs are sites of important events and stories (Harris, 1981; FOMS, 2019a; Hercus & Sutton, 1985).

Groundwater-dependent ecosystems (GDEs) in and around springs support fauna and flora of particular scientific and ecological importance, with some fauna species entirely restricted to individual springs or localised groups of springs (Kennard et al., 2016; Rossini et al., 2018). Recent studies have found 42 newly identified invertebrate species in the South Australian springs, with 25 of these species endemic to spring environments (Gotch, 2013). The values of physical structures, biological and cultural features and processes of springs are recognised nationally and internationally (Ordens et al., 2020).

Healthy springs require a very specific combination of surface structures, geochemical processes and flow regime to sustain their ecologically rare groundwater-dependent ecosystems. Spring flows are dependent on both groundwater pressure and the condition and conductivity of the spring vents. An increasing body of knowledge is defining the important characteristics which determine spring types, geomorphic features, flow regimes and dependent ecosystems (Keppel et al., 2015, 2016; Gotch et al., 2016; Love et al., 2013a, Love et al., 2013b; Kennard et al., 2016; OGIA, 2016).

This expanding knowledge has led to more detailed classifications and typologies of springs (Brake et al., 2020). Springs have been classified into a hierarchy ranging from spring vents, groups and complexes, to 13 supergroups (Gotch, 2013). Much more detailed information is now available on water sources and hydraulic environments, with clearer definition of which springs are fed by GAB groundwater, as distinct from more superficial or unconfined aquifers. Six types of structural linkage (geological/hydraulic) have been described for GAB springs, and seven categories of spring surface morphology have been identified (Keppel, 2013; Keppel et al., 2013; Keppel et al., 2016).

Greater understanding of ecological values of springs has resulted from the Allocating Water and Maintaining Springs in the Great Artesian Basin project, which incorporated multiple new investigations into biodiversity, distribution patterns and species richness in spring ecosystems (National Water Commission, 2013; Rossini et al., 2018). Springs are much more diverse ecologically than previously reported, with a high degree of endemism and little dispersal of most species between springs (Murphy et al., 2015).

GAB springs continue to have enduring cultural significance for First Nations people, and high economic value for GAB communities and for the wider Australian population as unique natural assets (GABCC, 2018; Frontier Economics, 2016). The GAB springs and bores have provided the only reliable source of fresh water for humans and pastoral stock, as well as for mining and outback towns, profoundly influencing the direction and extent of development of inland Australia following European settlement (Harris, 1981).

Management and Compliance

Management of GAB springs is the responsibility of jurisdictional agencies dealing with governance of land use, planning, water use, environmental conservation, soil conservation, agricultural and development activities.

Cooperative management of the basin included the co-funding of the Great Artesian Basin Consultative Council (GABCC) by basin governments and the Commonwealth in 1998. The first GAB Strategic Management Plan (SMP) developed a basin-wide non-statutory management plan collaboratively between governments and the Great Artesian Basin Coordinating Committee (GABCC, 2009). The SMP was the first 'whole-of-basin' management plan to be adopted by all governments responsible for the management of the GAB to address the critical issues and limitations in management identified by basin stakeholders (Brake, 2020).

The basin governments, including the Commonwealth with the support of the GABCC, co-funded the Great Artesian Basin Sustainability Initiative (GABSI) to assist landholders to cap and pipe uncontrolled bores (GABCC, 2018; DAWR, 2017). The GABSI cooperative investment of more than $300 million enabled the installation of 'closed water delivery systems', consisting of bore rehabilitation and replacement as well as the design and installation of pipe valves, tanks and troughs required to replace bore drains. GABSI and prior cooperative programs since the late 1970s have

successfully rehabilitated 759 flowing bores and converted 31,553 km of bore drain with piped systems, saving an estimated 235,640 ML of water every year and reducing the rate of pressure loss. However, the job is not complete; more than 535 uncontrolled bores and 6700 km of open bore drains are yet to be replaced by closed delivery systems. Ongoing maintenance of bores and water delivery systems is required to prevent a return to historical conditions (GABCC, 2009, 2010, 2018).

State water management plans set limits on the amount of water that can be taken, balancing new development with the needs of existing water users and the environment (Commonwealth of Australia, 2015). At the national level, the second GAB SMP covering the next fifteen years (2018–2033) was released for consultation in November 2019 (GABCC, 2018).

Threats to Spring Condition and Values

There are two primary threats to the values of GAB springs:

- The artesian pressure in the GAB which sustains the springs is being measurably reduced by the many thousands of bores sunk to reach the groundwater resource.
- Spring environments are being disturbed through physical destruction of geological features, loss of spring vegetation through grazing by stock and pest animals, increased nutrients from animal excretions, weed invasion and, in some isolated cases, through excavation.

Threats from Reduced Artesian Pressure

Water extraction from the GAB is effectively mining the water resource, given the natural and ongoing pressure decline and much lower recharge rates than previously estimated (National Water Commission, 2013). Flows from the springs are estimated to have decreased by at least 30% from flow rates at the time of European settlement due to development and extraction impacts, leading to pressure declines (GABCC, 2010; Commonwealth of Australia, 2015). It has been reported that more than 1000 springs have dried up as a result of GAB water extraction through artesian bores (SA Arid Lands NRM Board, 2017).

The major consumers of GAB water are mining and petroleum operations, including co-produced water, and pastoral use to supply water for stock (Brake et al., 2020). Towns and other users account for a minor volume. Both mining and petroleum operations are required to submit regular reports of water use to state agencies under their licence conditions.

Pastoral volumes for stock water are largely estimated from flow measurements on uncontrolled bores and conservative estimates on controlled bores, since springs are not easily metered.

Technical investigations are continuing to improve understanding of groundwater sources and connections and the rates of extraction by different sectors. Water use is generally licensed under water allocation plans developed by state agencies, such as licences issued by the responsible Minister for water extraction for stock water, mining and other purposes in the South Australian Far North Prescribed Wells Area.

Threats from Land Use

The majority of GAB springs remain subject to impacts associated with stock grazing, other agricultural activities and pest animals (Lewis & Harris, 2020). Springs subject to high grazing pressure from cattle and pest animals often receive high nutrient loading. Grazing animals can disturb or destroy geological structures associated with the springs, affecting or possibly blocking spring vents. Other deleterious impacts upon GAB springs include destruction of vegetation, impacts on fish (Kodric-Brown et al., 2013) and spring invertebrates, and changes to water chemistry (Shand et al., 2013). Physical damage, such as trampling and pugging in spring pools, can be severe, destroying plants, impacting insect habitat (Kovac & Mackay, 2009), disturbing the soil surface and creating multiple small pools with increased nutrients from manure and anaerobic conditions.

Historically, many GAB springs have been excavated, particularly in Queensland, with severe impacts on spring structures and ecosystems. Introduced plants are a problem at some springs (e.g. date palms at Dalhousie), while some springs have also been subject to visitor impacts, such as trampling of vegetation.

Adaptive Management Planning Process

There are three essential requirements for effective implementation of the Adaptive Management Plan to improve spring management practices:

1. Robust science that accurately characterises the nature, threats and condition of spring complexes.
2. Effective legislation and regulation to protect springs that define the rights and commensurate responsibilities of water users and land managers.
3. A culture of willing compliance that engages all water users and land managers in active protection of (agreed) spring values while enabling the productive use of GAB water and surrounding land-systems.

In developing an adaptive management planning process for GAB springs, the project team applied a logic that is applicable to a wide range of environmental management planning processes but targeted to the specific characteristics and values of the GAB and its springs. Management planning steps were described in some detail and then summarised in template form for ready reference. In broad terms, two major steps are involved, as summarised below.

STEP ONE: Determining the Need for a Management Response – Situational Analysis

The Springs Situational Analysis component assesses the current status of springs (Table 1), taking into account the following factors where relevant:

- Location and land systems.
- Land tenure and use.
- Features and values: geological, hydrological, ecological and cultural.
- Condition.
- Threatening processes, existing and potential.
- Regulatory framework relevant to springs management.

A combined appraisal of these factors is undertaken to provide a risk assessment – in effect an assessment of the probability of threatening processes having significant impacts upon spring values.

The first step includes evaluation of spring condition and the extent of threats to surface integrity or spring flows. A comprehensive study has spatially analysed the threats and risks to all springs in the GAB for which reliable data are available (Kennard et al., 2016). It involved a spatial assessment of biodiversity patterns and conservation values of discharge springs across the GAB and assessed the degree of conservation protection afforded to spring complexes and endemic species. The study identified 6308 springs in 326 spring complexes across 13 supergroups in the GAB and found that 5412 springs remain active, with the rest having ceased to flow. Springs were assigned a conservation rank (Fensham & Price, 2004) based on the status of endemic taxa and risks.

Where the risk assessment demonstrates that significant/unacceptable impacts are likely, this triggers the second component of the Adaptive Management process, the management response.

STEP TWO: Addressing Significant Threatening Processes – Adaptive Management Response

The Adaptive Management Template proposes a range of on-ground options to protect spring values by addressing the issues of artesian water pressure and surface impacts while causing minimum disruption to landholder operations. An appropriate management response will be negotiated between landholders and regulators based on an evidence-based spring monitoring and evaluation process. Table 2 provides an example of the decision framework, summarising some of the main management issues for GAB springs and options for management actions (the full table appears in Brake et al., 2020).

The GAB Adaptive Management Plan includes examples of management tools which have been applied at individual spring sites to address particular risks and the local situation. Installation of closed water delivery systems remains a high priority. Valuable lessons have been learned concerning drilling standards, planning and improved design and technology for water delivery infrastructure, as well as the necessity for cooperation and willing compliance (Brake, 2020). Ongoing work is required on cooperation, compliance and a coordinated policy between governments and landholders to ensure that bores are controlled and closed water delivery systems are maintained for stock watering infrastructure worth more than $3.5 billion across the GAB (Brake, 2020).

Table 1. GAB Springs Adaptive Management Template: Evidence-based methodologies for managing risks to spring values.

Springs Situational Analysis

Assessment of current status of spring complex

1. Spring complex characteristics:
- Location and land systems.
- Physical processes and structures.
- Natural values.
- First Nations cultural values.
- Historical and modern cultural values.
- Typology and scale of springs.

2. Legislation and Regulations:
- Land tenure.
- Water and Land Management Regulations.
- Current management and compliance.

3. Current condition and possible threatening processes:
- Management and proposed changes.
- Threats from water extraction.
- Threats from current land uses.

4. Evidence base for decision making:
- Assessment of current spring evaluation.
- Trends under current management.
- Evaluation to determine need for management response.
- Development of management approach.
- Proposal for negotiating on-ground actions and support.

Adaptive Management Response

Negotiated response based on situational analysis and coordinated strategies and options

5. Engagement for negotiating response:
- Landholders.
- Industries.
- Government managers.
- Indigenous groups.

6. Risk assessment – pressure loss:
- Risk from current and proposed extractions.
- Regional water extraction.
- Local water extraction.

7. Risk assessment – land uses causing surface disturbance:
- Mechanical disturbance.
- Grazing and pugging.
- Water quality.

8. Create a culture of willing compliance:
- Ensure shared knowledge of springs and threats.
- Consider industry and landholder needs.
- Share positive trends.

9. Risk management strategies to maintain spring flows:
- Ensure shared knowledge of springs
- Buffers and water extraction around springs.
- Regional extraction policy to maintain pressure.
- Maintain closed delivery systems.
- Ensure judicious use of GAB water.

10. Risk management strategies to protect surface structures, GDEs and cultural values:
- Control of grazing impacts.
- Management and monitoring agreements.
- Site management plans.
- Monitoring with reporting on change.

11. On-ground actions agreed between landholders, industries, Indigenous groups and governments:
- Formal agreements.
- Incentives, rewards and offset options.
- Shared funding arrangements.
- Compliance.

12. Implementation, funding and maintenance strategy:
- Long-term funding agreements.
- Framework for site agreements.
- Regular review of springs status.

13. Monitoring, evaluation and reporting:
- Standardised flow monitoring.
- Surface condition trends.
- Re-evaluation and adjustment.

14. Review and adapt management actions:
- Adaptive management loop.
- Review monitoring results.
- Build basin database.
- Fill information gaps.

Table 2. GAB Springs Adaptive Management Template: Example of Decision Framework for Major Threatening Processes.

Situational analysis						Response if action considered necessary				
Location and land use	**Spring types and values**	**Current condition**	**Threatening processes**	**Current regulatory framework**		**Strategies to manage risks**	**On-ground actions to address strategies**	**Implementation, funding and maintenance**	**Monitoring, evaluation and reporting process**	**Process for review and revision of actions**
Land use (e.g. grazing, other agricultural and conservation).	**Spring types** (e.g. travertine mounds, rocky seeps and terraces). **Spring values** (e.g. natural ecosystems, geological and cultural)	**Examples** *Very good*: Geological structures intact, no obvious disturbance of wetland biota. Steady flow: No apparent changes in wetland area. *Very poor*: Severe disturbance of geological structures and/or wetland vegetation and/or aquatic fauna. Flow may be significantly reduced, indicated by marked reduction in wetland area.	**Loss of pressure** Resulting from local or regional water extraction, leading to flow reduction at springs.	Some controls on artesian water extraction to protect spring flows. Environmental assessment for proposed new extractions. General protection under EPBC Act.	**Decision Point: Risk Assessment: Is action necessary based upon values, condition and threats?**	Management of regional and local water extraction to maintain pressure and spring flows. Rehabilitation of artesian bores, and maintenance of closed delivery systems.	Management of local water and regional water extraction. Bore and water infrastructure rehabilitation.	Clearly defined rights and responsibilities to protect spring values. Negotiated funding for infrastructure installation and maintenance: governments, water users and land managers. Land manager role in monitoring infrastructure and maintenance.	National, state and regional bodies to coordinate. Land managers and local groups may assist in routine monitoring.	National, state and regional bodies to coordinate in consultation with land managers and relevant local groups.
			Physical disturbance of spring environments Grazing, pugging, water pollution and excavation.	General duty of care provisions (e.g. under pastoral and natural resources legislation). Potential controls under native vegetation legislation regarding increases or changes in grazing pressure.		Exclusion of stock and introduced animals. Provision of alternative water sources where needed.	Fencing of spring groups or individual springs, or destocking of spring paddocks. Site-specific provision of alternative water where needed.	Collaboration between governments/ regional bodies, land managers and third parties. Management agreements to be developed. Primary funding through governments/ regional bodies/ other third parties. Land manager role in maintenance.	Regional Natural Resources Board (or equivalent) lead role in collaboration with state pastoral/ agricultural and environment agencies. NGOs, land managers and volunteer groups may assist.	Regional Natural Resources Board (or equivalent) lead role in collaboration with state pastoral/ agricultural and environment agencies. Land managers, NGOs and volunteer groups also involved.

The excavation of springs represents a severe form of disturbance. In many cases, restoration of excavated springs will not be a feasible option, although this may be considered on a case-by-case basis, particularly where some of the core structural or ecological spring features are still present. It is important that adequate regulatory provisions are in place to control any future spring excavations and to minimise disturbance of spring vents.

Another primary threat associated with declining flows is acidification of travertine mound springs (Shand et al., 2013). Evaporative processes in conjunction with oxidation can mobilise iron and sulphidic isotopes from mineral stores in spring deposits, with potentially devastating impacts for isolated and often rare ecosystems around springs. With reduced flows, sulphidic soils in the discharge zone become exposed and sulphuric acid develops, giving rise to extreme soil and water acidification with pH readings as low as 1, leading to destruction of plant and animal species in spring pools and tails.

Healthy GAB springs require cessation of uncontrolled access by stock and pest animals (Peck, 2020). Stock exclusion measures should preferably target groups of springs rather than individual springs. Two general approaches can be considered (Lewis, 2001). The first is reservation for conservation purposes, either as public conservation areas through state national parks and wildlife legislation, or through private conservation initiatives. The second option, for stock and feral animal exclusion on lands under private or leasehold tenure, allows protection of selected spring areas while retaining the same land tenure. This could involve taking entire paddocks out of production but is more likely to involve fencing of selected springs or spring groups (Figure 3). Alternative watering points for stock should be provided where needed.

Figure 3. Stock grazing at Levi Springs in the south-western GAB (above). In 2019, the same spring (below) showed rapid recovery only six weeks after stock-proof fencing was completed in cooperation with the pastoral lessees (Photos: C. Harris).

Monitoring, Evaluation And Reporting

Timely robust data and long-term monitoring data are key elements in understanding and responding to changes that risk spring health (Brake et al., 2020). A coordinated and funded national GAB springs monitoring program will be required to provide the necessary data for sound decision making on spring management and to collate all relevant springs data across the GAB region.

Monitoring the condition of springs serves two important functions in the proposed Adaptive Management process. First, in many instances it may provide evidence of declining condition of springs and help to identify where management interventions are needed. Monitoring at this stage may also indicate the nature of impacts and processes that dominate at particular spring locations (e.g. surface disturbance by grazing or reduction in flow). Second, after changes to spring management have been implemented, continued monitoring will be essential to assess their effectiveness. In addition, some spring protection mechanisms may require objective evidence of outcomes; focused research and monitoring data are needed to provide this vital evidence (Lewis & Packer, 2020; Peck, 2020).

Spring flow has often been used as a key indicator of spring status and condition, but it is highly variable on a diurnal, seasonal and annual basis (Love et al., 2013b) and very difficult to measure *in situ* in complex wetland environments. For spring-dependent ecosystems, the area of wetland communities supported by spring flow is the preferred ecologically relevant indicator of spring condition currently being used for monitoring some GAB springs. Considerable recent research has demonstrated the effectiveness of remote sensing approaches in objective, continued monitoring of spring groups in the arid western margin of the GAB (Figure 4; White & Lewis, 2011; Lewis et al., 2013; White et al., 2016). However, in higher rainfall areas of the eastern GAB, spectral mapping of springs can be more challenging as there is less contrast between spring vegetation and surrounding landscapes.

Figure 4. Remote sensing image demonstrating the spatial and spectral detail available for measuring and comparing the wetted areas in and around springs at selected time intervals to determine trends in condition of springs and their dependent ecosystems (Image: World View-2).

A comprehensive, coordinated, long-term monitoring program with committed funding will be needed to underpin the Adaptive Management Template and ensure sustainable management of GAB springs into the future. An objective, rigorous and cost-effective monitoring program will be essential to assess the condition of assets and the effectiveness of management actions (Sibenaler, 2010).

Review and Adaptive Management Actions

An adaptive approach to spring management is necessary because spring characteristics, surface conditions, GDEs and impacts of land use are highly variable. This process requires the operation of an adaptive management loop to assess the effectiveness of management actions and to check the need for any modifications or changes. New methodologies for cost-efficient, effective monitoring have been developed and tested, with promising potential for application basin-wide to monitor outcomes and to provide feedback on any adjustments needed to the risk management program.

Risk management strategies need to be fit for purpose, inclusive of the management of all identified impacts at a spring site, and tailored to a level appropriate to the risks and vulnerabilities of the particular spring type.

A robust, comprehensive and interactive basin-wide database will be critical to the successful implementation of an evidence-based Adaptive Management Plan for GAB springs. The database needs to combine all available information on spring characteristics, condition, trends, values, groundwater-dependent ecosystems, risk factors and their impacts. It also needs to create a basis for progressive monitoring and evaluation of outcomes as management interventions are put in place.

A baseline of the current condition of GAB springs is being established by Queensland and South Australian agencies, maximising use of existing data-sets and knowledge. This will need to be evaluated regularly and updated to assess spring status, values and trends in condition over time. Research needs to continue on particular issues, to fill identified data gaps, such as standardising classification of springs, tracking nutrient dynamics and the recovery of spring vegetation communities following stock exclusion by fencing springs (Lewis & Packer, 2020; Peck, 2020).

Accessible GAB Springs Information Platform – The Way Forward

In the future, a portal is proposed to be developed for the whole GAB to collate all available information on every spring and spring group, to make that knowledge accessible to managers and to support their decisions on appropriate actions to manage threats to springs (Brake et al., 2020).

A GAB Springs Stewardship Initiative (GABSSI) was developed in 2019 with the aim of providing ready access to attractive, interesting and compelling information about GAB springs, why they need to be cared for and the best way to care for them, through a range of interlinked information portals.

The GABSSI proposal is designed to ensure that ongoing adaptive spring management is welded-in as a key strategy in future governance arrangements and management priorities for the GAB. This, together with a GAB-wide coordinated database, is the next priority for securing the future of the GAB springs. This proposal is now an approved project in the SA State Work Plan for the Improving Great Artesian Basin Drought Resilience (IGABDR) 2020–2024 program, with work scheduled to commence in the 2020–2021 financial year.

Conclusions

The GAB Adaptive Management Plan and Template present evidence-based methodologies to assess and manage identified risks to spring groups across the GAB. These include requirements to install and maintain closed water delivery systems for extraction of water from GAB springs. Other options include retirement of whole pastoral paddocks with important spring clusters or fencing to exclude stock from high-value springs while providing alternative water points. There is also a key recommendation for a coordinated, basin-wide monitoring program to inform management of GAB water sources and springs. The principles underlying the Template are applicable to all spring types in all states across the GAB (Brake et al., 2020).

Securing the future survival of the GAB springs requires sound governance arrangements and bi-partisan commitment to ongoing management programs as well as secure funding. The second 15-year GAB Strategic Management Plan (2018–2033) provides a general policy basis for sound

governance. Each of the basin states has relevant supporting legislation and regulations to support this plan.

The GAB Springs Adaptive Management Plan aims to maintain artesian pressures that sustain spring flows and to encourage sensitive land-use practices in and around springs, while minimising disruption to current users of basin water resources. The Plan provides a framework for balancing productive use with protection of spring geology and ecology through the application of an evidence-based template that can be applied across the GAB to evaluate springs and negotiate water extraction practices.

The GAB Adaptive Management Plan and Template bring together relevant evidence from recent research and provides a decision framework for assessing the risks and determining appropriate management actions to address those risks. It is recommended that the Plan and Template be adopted as an implementation strategy as part of the Implementation Plan for the updated National GAB Strategic Management Plan (2018–2033).

Acknowledgements

The GAB Adaptive Management Plan and Template were developed during 2019 by an experienced project team and driven with enormous energy and dedication by Lynn Brake, to bring to reality his vision of securing long-term and well-funded future care for GAB springs. His leadership of the project and the energy he dedicated to the task, all the while battling serious health issues, were inspirational to the project team.

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Project team members were:

- Lynn Brake[a] – Senior Research Fellow, University of South Australia; founding member of the GABCC.
- Colin Harris – President, Friends of Mound Springs (FOMS).
- Simon Lewis – Secretary, FOMS.
- Travis Gotch – Chief Researcher in the National Water Commission study Allocating Water and Maintaining Springs in the Great Artesian Basin; Vice-President, FOMS.
- Professor Megan Lewis – University of Adelaide; Chief Researcher in the National Water Commission study Allocating Water and Maintaining Springs in the Great Artesian Basin.
- Associate Professor Andy Love – Flinders University Centre for Groundwater Studies; Chief Researcher in the National Water Commission study Allocating Water and Maintaining Springs in the Great Artesian Basin.
- David Leek – Principal Policy Officer, South Australian Department of Environment and Water.

Dr Mark Keppel, Senior Hydrogeologist, South Australian Department for Environment and Water, contributed the section on the hydrogeology of GAB springs.

The project team was supported by environmental consultant Dr Anne Jensen.

[a] Sadly, Lynn Brake passed away on 21 December 2019. On 19 December he was advised of the creation of the Lynn Brake PhD Scholarship for research on mound springs. On 20 December he was presented with his own personal print copy of the completed GAB Adaptive Management Plan and Template, which will be a key tool to continue his campaign to care for mound springs. His legacy will live on.

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Blanche Cup (*Thirka*) with extinct mound spring Hamilton Hill (*Wabma-kardayapu*) in the background. This area is the site of an Aboriginal Dreaming story relating to the Rainbow Serpent *Kanmari* (Photo: A. Jensen).

Author Profiles

Anne Jensen has worked on environmental issues through four different careers, in government environmental policy, coordinating Murray River on-ground wetland repair projects with a not-for-profit conservation company, undertaking academic research into environmental water requirements, and currently as a consultant on environmental projects.

Anne undertook environmental impact assessments for the sealing of the Stuart Highway from Pimba to the Northern Territory border in 1978–1983, through the south-western GAB. Later, she was manager of the Pastoral Branch 1989–1991 during the introduction of sustainable stocking rates to South Australian pastoral leases, many of which include GAB springs.

Anne is a member and former Vice-President of FOMS and contributed to the development of public walking trails at Strangways Springs and The Peake.

During 2019, she coordinated report production for the project team preparing the Adaptive Management Template for Mound Springs of the Great Artesian Basin.

Simon Lewis is a retired South Australian public servant, having spent most of his 34-year career in the State Environment Department. He first travelled to the GAB springs in 1977 and, from the early 1980s, coordinated the Department's spring fencing and vegetation monitoring program. He is a foundation member of Friends of Mound Springs (FOMS), established in 2006, and is the long-standing Secretary of that group.

With FOMS, Simon has coordinated annual voluntary monitoring visits to build on the government monitoring program with observations at 10 key spring sites in the south-western GAB, accumulating 35 years of data. He also contributed to the development, installation and maintenance of public walking trails at Strangways Springs and The Peake.

During 2019, Simon was a member of the project team which prepared the Adaptive Management Template for Mound Springs of the Great Artesian Basin.

Megan Lewis is Professor in Spatial Sciences in the School of Biological Sciences at the University of Adelaide.

Megan has an extensive background in remote sensing, vegetation ecology, and environmental science and management. She specialises in hyperspectral sensing for discriminating and mapping vegetation, soil and water properties, and assessing environmental condition and monitoring of environmental change with multi-temporal imagery.

She was a Chief Researcher in the National Water Commission study Allocating Water and Maintaining Springs in the Great Artesian Basin, published in 2013, and in the Lake Eyre Basin Springs Assessment studies for the SA Department for Environment and Water, completed in 2015.

During 2019, Megan was a member of the project team which prepared the Adaptive Management Template for Mound Springs of the Great Artesian Basin.

Springs of the Great Artesian Basin – Knowledge Gaps and Future Directions for Research, Management and Conservation

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Abstract

This Special Issue of 19 papers published by The Royal Society of Queensland is especially timely as Aboriginal Peoples, pastoralists, scientists, governments and conservation groups work towards the recovery of groundwater pressure, threat abatement and conservation of spring communities and species throughout Australia's Great Artesian Basin (GAB). Our introductory paper outlined contributions from individuals, sectors and perspectives, weaving a narrative around the major themes of the compendium. Here we summarise, often in the words of the authors, the next steps to fill fundamental knowledge gaps, implement management strategies, enhance mechanisms to conserve endemic species, and develop effective models of governance and stewardship. To conclude this synthesis, we bring to attention a recent "Plea for Improved Global Stewardship of Springs" (Cantonati et al., 2020) – a fitting framing for our summary of actions needed to revere, understand and protect the springs of Australia's GAB. These springs are among the most revered, structurally complex, ecologically diverse, evolutionarily unique and threatened groundwater-dependent ecosystems in Australia. We owe it to the many Aboriginal nations that comprise the GAB, all other life sustained by springs, and future generations of Australians to conserve these precious oases of life in Australia's arid, semi-arid and northern tropical regions.

Keywords: Great Artesian Basin, springs, cultural values, endemic species, groundwater-dependent ecosystems, aquifer drawdown, feral animal disturbance, alien species, governance and stewardship models, conservation and management frameworks, EPBC Act, 1999

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Introduction

Springs of the Great Artesian Basin (GAB) are sites of fascination and wonder as oases of life in arid, semi-arid and northern tropical landscapes of Australia. The majority, and certainly the most well-researched springs, are located in the more arid areas of these landscapes in Queensland, New South Wales and South Australia, and they are the focus of this Special Issue published by The Royal Society of Queensland.

Water springing forth from beneath inland desert plains is revered by Aboriginal Peoples, who have long cherished their inherent connection to the basin and its springs, soaks, shallow aquifers and Country. The chain of springs that extends from Kati Thanda–Lake Eyre to north-eastern

Queensland forms vital points in cultural lore and song-lines, and springs remain important sources of material and spiritual inspiration for traditional custodians (Ah Chee, 1995; Moggridge, 2020). Springs also served as a vital resource during early European exploration and occupation of inland Australia by providing reliable water supplies in essentially dry landscapes. During this time, as with pre-colonial times, springs served as nodes that facilitated exchange and communication across vast distances. They were instrumental in guiding the routes of the Overland Telegraph Line from Darwin to Port Augusta, and the Ghan railway from Darwin to Adelaide.

The discovery in the 1880s that settlers could dig wells and drill bores to exploit the waters of the Great Artesian Basin was pivotal for the emerging pastoral industry (Brake et al., 2020). However, colonial modes of management and exploitation quickly led to severe impacts on springs. Unlimited groundwater extraction through bores, excessive wastage through evaporation and seepage from bore drains, physical disturbance from introduced species and vain efforts to improve flow all contributed to a loss of 20% of springs over a short 200-year period (Fairfax & Fensham, 2002; Powell et al., 2015; Rossini et al., 2018). The loss of GAB springs is of concern because of their extremely high cultural and conservation values, and because their demise or inactivity is a sign of the broader issue of diminished pressure in the aquifer at large (Fensham et al., 2016).

Springs have been recognised worldwide as groundwater-dependent ecosystems of disproportionately high biological diversity (Cantonati et al., 2020). They form evolutionary refugia – permanent or semi-permanent groundwater-dependent habitats supporting rare and endemic species of plants and animals that have adapted and persisted over millennia (Davis et al., 2013; Murphy et al., 2015a). Springs that emerge from the GAB in Australia support a high diversity of endemic aquatic species. However, the majority of these endemic species have a high risk of extinction due to their small geographic ranges, severe habitat loss and ongoing threats to the groundwater-dependent wetlands they occupy.

Despite the unique nature of GAB springs, their many endemic species and the severity of the threats they continue to face, these groundwater-dependent ecosystems have only recently attracted formal conservation attention. The flora and fauna associated with springs came under Commonwealth protection in 2001, via the listing of "the community of native species dependent on natural discharge of groundwater from the GAB" as endangered under the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act, 1999). A Recovery Plan was published in 2010, with the overall objective to maintain or enhance groundwater supplies to GAB discharge spring wetlands, maintain or increase spring wetland habitat area and ecological health, and increase populations of all endemic organisms (Fensham et al., 2010).

Likewise, two decades have passed since the publication of the original national strategic management plan for the GAB (GABCC, 2000). Importantly, development of the national plan led to the first nationally coordinated basin infrastructure funding program, the Great Artesian Basin Sustainability Initiative (GABSI), commencing in 1999. These two national initiatives are now being renewed with greater vigour and focus on the importance of saving water, a major factor in improving spring health and conservation.

Over time, Australians have achieved a greater awareness of GAB springs as groundwater-dependent ecosystems, their endemic species, the processes that sustain them and the activities that threaten them. Yet there is no recent compendium of papers about the arid and semi-arid GAB springs and the prodigious efforts over decades to guide wise and respectful use of the groundwater resources of the basin. Likewise, the absence from this volume of papers about the springs of tropical northern Australia is a reflection of limited work on these systems, and another gap to be filled in GAB research and management.

This Special Issue of 20 papers published by The Royal Society of Queensland is especially timely as Aboriginal Peoples, pastoralists, scientists, governments and conservation groups work towards the recovery of groundwater pressure, threat abatement and conservation of spring communities and species throughout the GAB. Our introductory paper outlined contributions from individuals, sectors and perspectives, weaving a narrative around the major themes of the compendium (Arthington et al.,

2020). Here we draw out the major recommendations from those contributions. We summarise, often in the words of the authors, the next steps to fill fundamental knowledge gaps, implement management strategies, enhance mechanisms to conserve endemic species, and develop effective models of governance and stewardship. To conclude this synthesis, we bring to attention a recent "Plea for Improved Global Stewardship of Springs" (Cantonati et al., 2020) – a fitting framing for our summary of actions needed to revere, understand and protect the springs of Australia's GAB.

The Importance of Groundwater to Australian Aboriginal People

The Special Issue begins with an account of the importance of groundwater to Australian Aboriginal people, based on the research of Bradley Moggridge from the Kamilaroi nation in north-western New South Wales. Moggridge (2020) records the beginnings of his research on the relationships between Australian Aboriginal people and groundwater, with the intention "to inspire other Aboriginal people and researchers to take the subject matter further". Brad's telling of Dreamtime stories and rituals of caring for the land, water and all living beings illuminates our understanding of Aboriginal knowledge and affirms our profound cultural inheritance as new Australians. Unfortunately, the cultural significance of many GAB springs remains poorly documented, as other papers note (e.g. Silcock et al., 2020). This leaves valued artefacts and stories insufficiently recorded and protected (Pointon & Rossini, 2020). Traditions of passing knowledge along generational lines have also been lost, and what remains is under further threat from social changes and physical changes to spring country.

The importance of working with Aboriginal communities and custodians to achieve cultural and social outcomes is a central theme of the GAB springs Recovery Plan (Fensham et al., 2010) and the new Great Artesian Basin Strategic Management Plan (Department of Agriculture, Water and the Environment, 2020). Brad's paper and other contributions herein (e.g. Harris, 2020; Jensen et al., 2020; Silcock et al., 2020) reinforce the imperative to integrate knowledge and wisdom from all sources, including that held by the original custodians of springs country, in spring investigations, management and conservation.

Hydrogeology and Hydrochemistry of GAB Springs

Habermehl (2020) provides an introductory hydrogeological foundation on groundwater flow patterns and ages, discharge from artesian springs and spring deposits, drawing upon the history of extensive hydrogeological investigations and numerous studies that characterise the groundwater sources supplying various GAB spring complexes. The paper illustrates the remarkable variety of spring formations, such as the conical mound springs and travertine terraces in the south-western parts of the basin. Investigations reviewed therein highlight the importance of understanding the relationships between springs and their source aquifers, and the hydrogeological processes that create and maintain springs in the arid environments of the Great Artesian Basin.

Although numerous studies characterise the groundwater sources supplying various GAB spring complexes, uncertainties remain in some areas of the basin. This uncertainty has implications for water allocation, groundwater resource management and the protection of spring wetlands.

Through discussion over the last decade of advancing spring knowledge in the Surat Basin, Flook et al. (2020) describe the application of hydrogeoecological survey data in developing detailed conceptual models of springs and their associated wetlands, and in designing monitoring strategies to better understand spring dynamics and responses to groundwater drawdown. The paper highlights the importance of understanding the drivers of the observed dynamics at springs and their criticality for determining appropriate monitoring strategies and for understanding how changes in groundwater pressure could affect wetland ecosystems. In parallel, the paper highlights how understanding changes in abundance and distribution of associated biota can be more meaningfully achieved through further unpacking of the spring water balance.

Using groundwater hydrochemistry and environmental tracers, Keppel et al. (2020) identifies the likely sources of groundwater supporting the Lake Callabonna and Lake Blanche spring complexes in South Australia for the first time. His identification

of the RDGS (Rolling Downs Group Sandstone) aquifer in the region has important ramifications for understanding the hydrogeology of the GAB. The paper recommends hydrochemical modelling, such as a mixing model, as a necessary next step to identify the potential for, and to quantify, mixing between different groundwater sources: "Given the prevalence of ecologically sensitive spring environments, as well as established pastoral and petroleum industries in the region, management and regulation of groundwater affecting development requires a refocus from predominantly a single aquifer to potentially multiple aquifers."

Surveys continue to yield new information in the less well-studied parts of the GAB, such as the Mulligan River springs, the only permanent surface water in this dry region on the edge of the Simpson Desert in far-western Queensland (Silcock et al., 2020). This paper explores the hydrogeology, cultural history and ecology of the Mulligan River springs using historical maps, journals, diaries, letters and newspaper articles from early explorers, pastoralists and travellers, and interviews with the managers of contemporary pastoral stations. Recent surveys document the biota and current condition of these remote springs, and we learn that the Mulligan River springs are different from most GAB springs in the lower diversity of their flora and fauna, and absence of endemic species. Silcock et al. (2020) recommend further work to elucidate spring hydrogeology, particularly with regard to projected water use by extractive industries in the Eromanga Basin, and understanding spring dynamism and apparent recovery of some springs after bore capping. Furthermore: "Detailed archaeological work at the springs would provide further insights into Aboriginal use of the springs, including their place in the broader cultural landscape and potential significance to Aboriginal trade networks in inland eastern Australia."

Ecology and Conservation of Spring Biota

Springs of the GAB are renowned for the richness and endemicity of the native aquatic species that occupy their wetland habitats. Despite their high conservation value, many of these species are at risk of extinction due to their small geographic ranges, severe habitat loss and ongoing threats (Rossini et al., 2018; Rossini, 2020). As small geographic range appears to be the norm, it is probable that severe biodiversity losses accompanied the broad-scale loss of springs that occurred post 1890 (Fensham et al., 2010). Habitat loss that has not led to extinction is still associated with the loss of genetic diversity (Faulks et al., 2017) and the potential loss of cryptic species or clades before they are discovered or described (Mudd, 2000). Our ability to conserve these species depends on knowledge of their distributions and environmental needs, yet we lack such information for the vast majority of species (Rossini, 2020). In this volume, five papers advance our knowledge and enrich our understanding of the patchy distribution patterns, special habitat requirements and conservation status of some of these unique spring species (Choy, 2020; Clifford et al., 2020; Kerezsy, 2020a,b; Rossini, 2020).

Core to understanding and conserving springs is sound knowledge of their biota. The unique evolutionary histories created by disjunct distributions across the basin's springs create complex evolutionary quandaries. Many researchers who dive into these questions find complexes of cryptic species (Murphy et al., 2009; Murphy et al., 2015b), surprising patterns of population structure (Wilmer et al., 2008; Worthington-Wilmer et al., 2011) and, more often than not, new species. Species new to GAB springs are being described at a rate of two per year, at present, with many invertebrate species known as putative endemics but still awaiting formal description. Choy (2020) presents a case study of one of these. The "enigmatic" freshwater shrimp – *Caridina thermophila* – is found in GAB springs at only four locations within the Barcaldine supergroup. Choy concludes that "… very little is known of the exact taxonomic status, distribution, demography (population size, structure, natality and mortality rates) and ecology of this species". This is not unique, as detailed by Rossini (2020), and has major consequences for how effectively we can conserve species in GAB springs (Pointon & Rossini, 2020).

In some cases, spring species are taxonomically well defined, and their distributions are relatively well known. To understand how threatening processes may impact them, we need autecological summaries, which for many species are woefully inadequate or absent altogether (Rossini, 2020). Kerezsy (2020a) shows how an ecological account

of a particular species, its distribution and its environmental requirements can be achieved. He builds on a legacy of field ecology concerning spring species (e.g. Ponder et al., 1989; Rossini et al., 2018; Rossini, 2020). Taxonomy is the first step on a long journey towards understanding spring species, but without data on how these unique organisms associate with, and rely on, their distinctive habitats we cannot communicate or predict how threatening processes may impact them. We are also missing the unique stories each of them can tell about changes in our continent's environment, and how life finds a way to persist in new ways. As summarised by Kereszy (2002b): "Persisting as they do in such unique and specialised habitats, the study of these GAB fish species – and all GAB springs endemics – can reveal much about evolution, speciation and resilience. It is therefore imperative that we respect and conserve them and their unusual habitats."

Kerezsy (2020b) and Rossini (2020) present syntheses of the conservation status of two large groups of spring taxa that present very different conservation challenges. The fishes endemic to springs, as summarised by Kerezsy, are relatively well studied, and whilst the ecological knowledge of some species is limited, he has been able to present an overview of the present conservation status of this group. In contrast, the invertebrates represent the most diverse but least taxonomically resolved and least protected group of spring inhabitants. Rossini (2020) documents risks, fundamental data deficiencies and inconsistencies in the process of listing invertebrates under EPBC Act criteria (the most speciose group of endemics). Using gastropods endemic to the Pelican Creek Springs complex as exemplars, she illustrates challenging issues around accurate estimation of two vital metrics: geographic range (EoO – extent of occurrence) and the habitable or inhabited area (AoO – area of occupancy). The analyses of her paper provide support for all species of gastropods and crustaceans to be listed and hence protected individually under the EPBC Act. Further discussion of the efficacy of the EPBC Act to conserve and protect springs and their endemic biota comes later in this synthesis (Pointon & Rossini, 2020).

These ecological papers present an overview of how knowledge of the biological values of GAB springs has, and can continue, to grow. They stand as important baseline references for other contributions to the Special Issue regarding threats, adaptive management plans and mechanisms to ensure protection. It is impossible to understand the potential impacts of threatening processes – historical, contemporary or predicted – without knowledge of how GAB species respond to and rely on elements of a spring's environment. Adaptive management plans cannot monitor nor correlate changes in a spring's community with changes in the environment without this baseline data. Furthermore, legal protective mechanisms cannot function effectively without up-to-date understanding of conservation risk or the potential impact of proposed project activities. Through these contributions we hope that the power of ecological enquiries into GAB spring ecosystems and their biota is recognised, emphasised and further studies are supported.

Threats to GAB Springs and Their Biota

Threats identified in the GAB springs Recovery Plan include: aquifer drawdown; excavation of springs; stock and feral animal disturbance; alien (introduced exotic) species of plants and animals; tourist visitation; and development of impoundments (Fensham et al., 2010). This Special Issue stands as an opportunity to review some of these threatening processes, and to provide examples of how activities and research over the past decade have sought to understand and reduce their impacts on springs. Here we summarise the findings and recommendations of papers that address three major threats given emphasis in the springs Recovery Plan: aquifer drawdown, feral animal disturbance and alien species.

Aquifer Drawdown

Scientific exploration and development of the GAB commenced following the construction of the first artesian bore in 1878. A vast system of open artificial channels, known as bore drains, was constructed to distribute flowing water to individual or groups of pastoral properties, often over significant distances. The benefits for settlements and the growing pastoral industry were enormous, but gradually gave way to concerns about declining bore pressure, water losses to evaporation, and adverse effects on spring ecosystems.

Brake (2020) describes the effects of water

extraction and use on artesian pressures and bore flow rates, and the history of efforts to control flowing artesian bores and reduce wastage of the GAB water resource via GABSI and other programs. The Great Artesian Basin Sustainability Initiative (GABSI) was centred on artesian pressure recovery, sustaining GAB spring flows and assisting landholders in the rehabilitation of bores and water delivery infrastructure. Brake (2020) concludes that although GABSI achieved its major objectives over nearly two decades, and has been very successful in supporting the transition to closed water delivery systems, it is not complete. There are now more than 50,000 bores in the GAB, of which 6600 are artesian bores, and at least 430 of these bores remain uncontrolled. He notes that if the true return on the investment is to be understood, "reliable information on the broader inputs and outcomes of GABSI beyond just dollar cost of water saved needs to be investigated".

In a 2010 benefit-transfer study, Rolfe (2010) estimated the off-farm benefits of improving the management of the GAB to be at least as high as $17.8 million per year, outweighing the annual program costs of $15.5 million per year from the Australian and state governments in Stage 2 of GABSI. Off-farm benefits accrue to different societal groups and interests, including recreation, tourism, biodiversity assets and cultural heritage, options for future use and conservation, and reductions in greenhouse gases. Information on these benefits will provide "key evidence needed to guide future management and investment decisions concerning the taking of water from the valuable GAB resource in the future" (Brake, 2020).

Effects of Exclusion Fences Around Springs

Grazing by native species is a natural feature of spring ecology and can be essential for maintaining microhabitat and species diversity (Unmack & Minckley, 2008). However, springs can be seriously affected by over-grazing and habitat disturbance caused by livestock and feral species (pigs, camels) as well as native animals (Fensham et al., 2010). De-stocking, and fencing around GAB springs to exclude stock and feral animals, are well-established management approaches for protecting springs of high conservation value, especially in situations where baiting, shooting and mustering fail to provide sustainable outcomes (Negus et al., 2019).

Unlike the GABSI initiative designed to tackle groundwater drawdown, efforts to fence springs have been local and strongly dependent on strong support of land managers or community groups. Two contributions included here present excellent documentation of the impacts of fencing springs to alleviate the threat of disturbance by stock and introduced species. The Eulo Springs supergroup is one of the most taxonomically rich but least understood spring complexes in the GAB (Rossini et al., 2018). Peck (2020) documents a program where feral animal activity was managed effectively through appropriately designed exclusion fences. Through qualitative condition assessment he shows that when feral animal activity is well managed, artesian spring wetland communities have a considerable capacity for recovery. Peck amply demonstrates that qualitative assessment methods have proved useful for local management staff to gather, collate and interpret data about spring condition on a routine basis.

In a data depauperate system, where on-country managers are often the people with best access to such remote locations, simple yet effective monitoring tools are essential for tracking how the system responds to threat mitigation. Peck (2020) suggests that these scoring techniques have potential to provide early-warning signals of changes in spring condition that should be assessed using quantitative ecological surveys and further research. Many springs in the GAB are located on private property (Harris, 2020), and numerous springs we need to protect to ensure the persistence of the majority of endemic taxa are managed by people who live on productive landscapes. Fencing, therefore, can be a useful tool for protecting high-value springs where the acquisition of an entire property under a conservation arrangement is not possible. Monitoring of these remote but valuable springs can provide vital data (Rossini et al., 2016), and Peck (2020) has demonstrated how simple monitoring frameworks can allow on-country managers to document how a threat mitigation practice is creating positive outcomes for their springs.

Threat mitigation like fencing does not always result in a predictable or ecologically positive outcome. Increases in the abundance and biomass of particular plant species following stock exclusion

by fencing can result in competition with other native vegetation, alterations to microhabitats, increased transpiration and loss of areas of open water habitat. Lewis & Packer (2020) present 35 years of observational data on the response of the common reed (*Phragmites australis*) and other spring vegetation, following exclusion of stock. This study highlights a unique situation, where efforts to mitigate a threat arising from past land-use change has created another threat through changed dynamics of a native plant.

Phragmites australis is a tall perennial grass native to Australia but with a cosmopolitan distribution; it forms monodominant stands in many wetlands throughout temperate and dryland regions of the world (Packer et al., 2017). The GAB study is remarkable for its longevity. It has shown that the dominance of *P. australis* waned in some springs after 30+ years of stock exclusion and, in another case, has not colonised a spring free of *P. australis* at the time of de-stocking, despite the presence of source populations in a neighbouring spring. These authors document how shifts in the abundance of *P. australis* have inevitably had impacts on another spring plant of conservation concern, *Eriocaulon carsonii*. This listed endemic GAB springs plant appears to have been reduced in distribution and abundance where *P. australis* has become monodominant. This long-term study highlights the necessity to commit to post-intervention monitoring like that presented by Peck (2020). Without it, such subtle impacts and emerging unpredicted threats with decades of latency may be overlooked, creating new threatening processes for more vulnerable spring taxa.

In their discussion, Lewis & Packer (2020) recommend experimental fencing of a landscape mosaic of springs with and without *Phragmites*, and monitoring of nutrient levels (elevated over time by stock excreta) to test predictions of their influence on the performance of *Phragmites*. Admirable efforts to control *P. australis* in the Irrawanyere (Dalhousie) springs have also demonstrated how First Nations management with fire can help return the balance in favour of endemic species and their habitat. Both Peck's and Lewis & Packer's contributions emphasise how the monitoring of threat abatement actions is essential and can be a relatively simple and accessible task.

Ecology and Control of Alien Aquatic Species

Aquatic species introduced to Australia from other continents have colonised many freshwater habitats, including GAB springs and bore drains. One of these has received significant focus in spring research as its impacts are of major concern (Pyke, 2008). The alien eastern gambusia (*Gambusia holbrooki*) is a small, aggressive live-bearing fish that was first introduced to Australia for control of larval mosquitoes. It has spread widely in Australia, feeds opportunistically across aquatic food chains, and now threatens the persistence of the critically endangered red-finned blue-eye (*Scaturiginichthys vermeilipinnis*) in Edgbaston (*Byarri*) Springs (Kerezsy & Fensham, 2013). This conservation reserve was purchased by not-for profit conservation group Bush Heritage Australia in 2008 to protect its springs and biota. Efforts to reduce *Gambusia* populations using Rotenone, a plant-based toxin, and removal of the red-finned blue-eye to predator-free habitat, have had measurable success at Edgbaston (Kerezsy, 2020a,b; Kerezsy & Fensham, 2013). However, gastropods and crustaceans may be susceptible to rotenone.

Edgbaston (*Byarri*) Springs is home to a second endangered fish, the goby (*Chlamydogobius squamigenus*). Surveys to establish its wider distribution in and around Edgbaston Reserve produced a surprising discovery – gobies are living in bore drains at Ravenswood, approximately 20 km from their natural spring habitat at Edgbaston (Kerezsy, 2020a). Kerezsy suggests that management of such an endangered species could involve a suite of unconventional methods, e.g. "retaining populations in artificial environments that utilise GAB water but otherwise are physically different from GAB springs". This option for conservation of a spring-dependent species has prompted an important policy question. Should some bore drains be left open (unpiped) to provide 'insurance' habitat for endemic species faced with threats in their natural spring habitat? In this instance, relying on bore drains as insurance habitat for the endangered goby is risky because all bore drains sampled by Kerezsy (and the great majority of bore drains in central-western Queensland) have been colonised by eastern gambusia. Tracking competitive interactions and responses of red-finned blue-eye and Edgbaston goby to *Gambusia*, and further

experimental studies to control this alien species, should be a priority. More broadly though, should artificial habitats that have developed a new aquatic ecosystem over time be protected when they help conserve endangered or other high-priority species? "This survey demonstrates that endangered species, despite being disadvantaged by small populations, limited suitable habitats and the imposition of invasive species, are sometimes capable of persisting in less-than-perfect circumstances. To enable such species to endure, and to improve these circumstances as much as possible, should therefore be the aim of all endangered species programs and recovery plans."

Another alien pest that has received less attention is the cane toad (*Rhinella marina*). This species also threatens the conservation of GAB spring ecosystems at Edgbaston (Clifford et al., 2020). Cane toads are opportunistic feeders, taking aquatic as well as terrestrial invertebrates. At Edgbaston Springs their gut contents were dominated by aquatic invertebrates, especially Coleoptera and endemic species of Gastropoda, with small intakes of Acarina, Amphipoda, Diptera, Epiprocta, Hemiptera, Hirudinea and Oligochaeta. Clifford et al. (2020) recommend further dietary analyses to determine seasonal patterns of cane toad foraging behaviour and the ongoing impact of these amphibians on spring ecosystems.

The occurrence of two vertebrate pests with opportunistic feeding behaviours and a preference for aquatic invertebrates (including endangered species) in this precious conservation reserve is particularly worrying. The case presented by Clifford et al. (2020) reiterates the importance of ecological studies to aid understanding of the mechanism by which a threatening process can act. The Edgbaston Springs complex is one of the most data rich in the GAB – and an exemplar of how research informs management and conservation. Publications concerning the impact of *G. holbrookii* on the critically endangered red-finned blue-eye (*Scaturiginichthys vermeilipinnis*) have drawn serious conservation attention to this species' plight, leading to direct and innovative conservation interventions. However, like cane toads, *G. holbrookii* also consume other elements of the endangered GAB-dependent community, especially invertebrates. As outlined by Rossini (2020), invertebrate taxa are poorly documented, often their taxonomy is unresolved, and they are inconsistently protected by conservation listings. Clifford et al. (2020) highlight another emerging and poorly understood threatening process that will be difficult to manage.

Recovering Springs

Although many discussions of conservation action in this Special Issue focus heavily on the role of policy and basin-scale initiatives, two papers remind us of the powerful role of citizens in understanding threats and protecting springs. These efforts can be overlooked by academic science or high-level policy initiatives. Impacts and histories are best documented as stories – in some cases decade-long stories. These stories emphasise the critical role of the human connection to springs in ensuring their conservation. Springs across the Great Artesian Basin hold stories of unsung heroes, from First Nations Peoples since time immemorial, through long-term commitments of dedicated individuals and groups, to emerging partnerships.

Harris (2020) describes five decades of 'watching mound springs' through professional activities and engagement with many key scientists and Aboriginal custodians of South Australia's mound springs. He recalls the interest and controversy surrounding the Olympic Dam Mine project developed to mine world-ranking quantities of copper, uranium, silver, gold and rare earth elements. Later in life he formed the community group Friends of Mound Springs (FOMS). As Founding President, Harris (2020) guided many activities focused between Marree and Oodnadatta in South Australia. A sister group, Friends of Simpson Desert Parks (FOS), supports spring protection at Dalhousie Springs.

FOMS has won many awards for biological and heritage conservation work at GAB springs. Travelling with Harris (2020) on his journey through five decades of involvement with mound springs in South Australia reveals a fascinating history of discoveries and yields many wise insights. He concludes that to consolidate the gains of the past and do things better into the future, we will "certainly need to involve regional stakeholders far more than has been the case hitherto, the pastoral lessees especially, as it is on their stations that most

of the unprotected springs occur. And we will certainly need to use the knowledge and connections to the land of its traditional owners more effectively. The legal niceties of Native Title aside, Indigenous people hold moral title to the land, and it is incumbent that we all work together to conserve these remarkable features of our inland landscape."

Edgbaston (*Byarri*) Springs and the ongoing conservation programs are shining examples of how the FOMS legacy is growing and expanding. To protect the springs and endangered fish species, Bush Heritage has installed fish barrier fences to either contain *Gambusia* populations or protect red-finned blue-eye populations from invasion. Red-finned blue-eye have been relocated to other springs to expand their range and the number of springs they occupy. Another strategy has been to establish 'insurance' populations onsite by diverting the outflow of an existing bore into artificial springs. Much of this effort has been supported by volunteers from diverse sources brought together to work with a shared passion to save endangered species and conserve the spring wetlands on which they depend. Engaging volunteers in conservation works at Edgbaston (*Byarri*) Springs has been hugely beneficial, not least because not-for-profit conservation projects need human resources for labour-intensive projects. Volunteers gain fieldwork skills and experience, and the whole enterprise fosters a sense of community and belonging by engaging universities, agencies and the general public in conservation works (P. Kern & L. Hale, pers. comm., 2020).

Spring Regulation and Policy

Legal Protection

The "community of native species dependent on natural discharge of groundwater from the Great Artesian Basin" is protected under Australia's main environmental law, the *Environment Protection and Biodiversity Conservation Act 1999* (Cth) (EPBC Act, 1999), and the 2013 EPBC Act amendment (the "Water Trigger") establishes water resources as a "matter of national environmental significance" (MNES) in relation to coal seam gas and large coal mining development. Whilst the advantages of these legal umbrella instruments are clear, the level of protection they offer to individual spring species bears scrutiny (Pointon & Rossini, 2020). Only a few species are individually listed (e.g. as endangered) under conservation legislation even though their vulnerability to threatening processes is well known from taxonomic studies, field collections and risk assessments (Ponder, 1995; Fensham & Price, 2004; Kennard et al., 2016). Pointon & Rossini (2020) review the strengths and limitations of the EPBC Act as it applies to the conservation of GAB spring species and the particular features of their biological communities. The paper highlights four complexities associated with the application of the EPBC Act to the management and conservation of GAB springs: the high level of discretion in decision making; data deficiencies that make it difficult to determine whether impacts are sufficiently "significant" to trigger assessment via an environmental impact statement (EIS); the flaws in offset management and mitigation measures; and the fact that community listings may not adequately protect individual species.

Although not GAB springs, a recent case study of Doongmabulla Springs illustrates how these legislative complexities have been addressed under the requirements of the EPBC Act in relation to development of a major coal mine in their vicinity. The Adani Carmichael Coal Mine Project (the project) has been approved at a site approximately 11 km from Doongmabulla Springs, north-west of Emerald in Central Queensland. Protecting these springs from activities associated with this mining development is an important requirement of the project approval. Doongmabulla Springs is a sacred site of the Wangan and Jagalingou Peoples, where the *Mundunjudra* (Rainbow Serpent) travelled to shape the land, rivers and springs. Furthermore, the springs are known to harbour species native to the endangered community dependent on GAB groundwater flows, yet there remains some uncertainty around the source aquifer for Doongmabulla Springs (Currell, 2016). Predictions of drawdown have been challenged, and there is grave concern for the future of these springs (Currell et al., 2017). The paper articulates the challenge of protecting the unique cultural and biodiversity values of springs alongside the ongoing demand for mineral resource development.

Pointon & Rossini (2020) conclude their paper with recommendations to enhance environmental impact assessment, project approvals, and the conditioning, monitoring and reporting of

the regulatory processes designed to protect the threatened springs and groundwater-dependent ecosystems of the GAB. They end on a cautionary note: "While scientific effort is slowly building an understanding of GAB ecosystems, failure to strengthen the regulation of impacts on springs and their communities may mean that these efforts merely document the decline of springs and the extinction of species reliant on spring habitats and resources."

Local Management Initiatives

Listing of the GAB springs community as endangered under the EPBC Act has the potential to protect a large, complex and fragmented system of wetland habitats and species that would be difficult to protect solely by elements of the Australian protected area network, such as national parks and other elements of the national estate. Some high-value springs and endemic species are afforded protection as part of large national parks or conservation areas (Rossini, 2020), but the majority are located within large properties under pastoral lease for cattle production. Threats to these springs persist in spite of numerous studies and risk assessments, the bore capping programs, management activities (e.g. fencing springs, pest control) and mechanisms under jurisdictional governance (water allocation plans). Yet a decade on from the release of the GAB Springs Recovery Plan in 2010, critical issues associated with the conservation and management of GAB springs persist, especially on pastoral lands.

Lewis & Harris (2020) review these critical issues in South Australia, where GAB springs located on pastoral lands are subject to vegetation destruction, pugging and pollution by stock and pest animals, leading to habitat degradation and loss. They propose a collaborative GAB springs conservation program involving state government agencies, pastoral lessees and others through application of management agreements under the South Australian *Native Vegetation Act 1991* or *Natural Resources Management Act 2004*, supported by financial backing through the NRM Water Levy for the region. While not directly transferable to other jurisdictions, this program sets out important framing elements based around robust data systems, identification of priorities for conservation, incentives for landholders, initial protection works, ongoing maintenance of protective measures, and a regulatory framework that underpins the incentives program, manages monitoring and compliance, and also provides security for the protective measures by means of a covenant or similar mechanism. Importantly, the authors recommend that the desired management targets for GAB springs should be:

- Springs functioning with the maximum diversity of native flora and fauna present, with species of particular significance conserved, geomorphological features protected, and with natural ecological processes occurring.
- Rationalising stock access to water in areas where springs have historically been an integral stock-watering resource in property management.

Great Artesian Basin Adaptive Management Plan

Most of the recent management efforts in the Australian natural resources sector have sought to bring stakeholders, research groups and management agencies together under an integrating and inter-governmental framework. The GAB Adaptive Management Plan and Template described by Jensen et al. (2020) follows this model. This plan was the final outcome of extensive collaboration between the (then) Australian Government Department of Agriculture, and sector agencies from South Australia, New South Wales, Queensland and the Northern Territory. It was developed during 2019 by an experienced project team driven with enormous energy and dedication by Lynn Brake, who brought to reality his vision of securing long-term and well-funded future care for GAB springs (Brake et al., 2020). His leadership of the project and the energy he dedicated to the task, all the while battling serious health issues, were inspirational to the project team. This team, managed by Natural Resources SA Arid Lands, brought many of the authors of papers in this volume together to forge a master plan for springs management and conservation.

The GAB Adaptive Management Plan and Template presents evidence-based methodologies to assess and manage risks to spring groups across the GAB while minimising disruption to current users of basin water resources (Jensen et al., 2020). The

principles underlying the Template are considered applicable to all spring types in all states across the GAB (Brake et al., 2020). A GAB Springs Stewardship Initiative (GABSSI) was developed in parallel, with the aim of providing ready access to attractive, interesting and compelling information about GAB springs, why they need to be cared for and the best way to care for them, through a range of interlinked information portals: "This, together with a GAB-wide coordinated database, is the next priority for securing the future of the GAB springs." Jensen et al. (2020) recommended that the Plan and Template be adopted as part of the Implementation Plan for the updated national Great Artesian Basin Strategic Management Plan (2018–2033).

Concluding Recommendations

As this synthesis paper for the Springs Special Issue was about to go to press, *Conservation Biology* published a paper entitled "Plea for Improved Global Stewardship of Springs" (Cantonati et al., 2020). It concludes with this powerful message:

> At a global scale, public awareness and active conservation are needed to reverse the conservation crisis facing springs and associated groundwater as human population pressure increases. Given their significance as biodiversity havens for many rare and endemic species, their keystone ecological functionality within landscapes, their extraordinary cultural and socio-economic values, and the relatively low cost of appropriate management (Knight, 2015), improving the stewardship of spring ecosystems and their supporting aquifers will yield substantial environmental advantages and societal benefits.

To conclude this synthesis of the springs Special Issue, we offer the following summary of actions needed to revere, understand and protect springs of the GAB, including the poorly studied springs of the northern basin, and likewise, springs with different groundwater dependencies and ecological communities throughout Australia. Our summary is framed around the plea's four key objectives and associated action items, and shaped by the recommendations of the Special Issue authors:

1. Recognise GAB springs as a distinctive group of groundwater-dependent ecosystems that warrant special conservation and public attention:
   - Reinforce and amplify basic understanding of springs, the water sources that sustain them, and their unique biodiversity as pivotally important Australian conservation targets.
   - Increase public and political awareness of springs as crucially important groundwater-dependent ecosystems and environmental indicators of the cultural and environmental health of the GAB.
   - Expand and support mechanisms to enhance understanding and documentation of GAB Aboriginal history, Dreamtime stories, sacred sites, language, cultural wisdom, and ecological and hydrological knowledge.
   - Institute models of co-management that empower Aboriginal Peoples to share in the documentation, management and restoration of springs.
   - Expand engagement, communication, outreach and informed debate about springs among all stakeholders.
2. Develop cultural and scientific guidelines and collaborative efforts to improve aquifer and spring stewardship across the GAB:
   - Reinvigorate and support social and biophysical research to develop conservation criteria that emphasise identification and protection of specific cultural sites, spring groups, and spring-dependent species of highest conservation value and risk.
   - Enhance and support spring and aquifer information management resources, e.g. the GAB Springs Stewardship Initiative (GABSSI) and a GAB-wide coordinated database.
   - Develop GAB-wide networks of reference locations with diverse spring types, threats and restoration initiatives, preferably within the framework of Australia's Long Term Ecological Research Network – LTERN (https://www.ltern.org.au).
   - Use LTERN sites as research and educational sentinel sites to monitor and test spring restoration strategies, and

to elucidate spring responses to human impacts, including climate change.

3. Identify, promote and fund culturally and scientifically proven methods for aquifer, spring and biodiversity management, conservation and restoration:
   - Ensure that spring GDEs are included in environmental flow assessments, procedures and regulatory frameworks.
   - Increase research and understanding of the physical and ecological impacts of resource development activities.
   - Expand and support experiments to test alien pest management strategies, conservation plans to recover endemic species, and spring ecosystem recovery programs.
   - Evaluate options for protecting endemic species in non-natural spring environments, bore drains and artificial habitats, or through translocation.
   - Expand and support cultural traditions, educational activities, research degrees, volunteer engagement and training, and NGO support networks.
4. Explicitly include springs in regional, national and international management directives, including enhancement and implementation of existing agreements:
   - Strengthen actions to protect springs via the Recovery Plan for the GAB springs endangered community, by means of the following: jurisdictional conservation legislation and water management plans; Commonwealth conservation legislation (MNES under the EPBC Act and the "Water Trigger"); the Ramsar Convention; and the IUCN Red List of Threatened Species.
   - Apply and test the GAB Adaptive Management Plan and Template and its evidence-based methodologies to assess and manage risks to springs across the basin.
   - Encourage and support Indigenous, scientific and public communities to lobby decision-making political entities for action towards enhanced legislation and management protocols for the protection of GAB groundwater resources, springs and individual threatened endemic species.

Springs of the GAB are among the most revered, structurally complex, ecologically diverse, evolutionarily unique and threatened groundwater-dependent ecosystems in Australia. In the spirit of reconciliation, we owe it to the many Aboriginal nations that comprise the GAB, and all other life sustained by springs, to conserve these precious oases of life in Australia's arid, semi-arid and northern tropical regions. A similar commitment is owed to future generations of all Australians.

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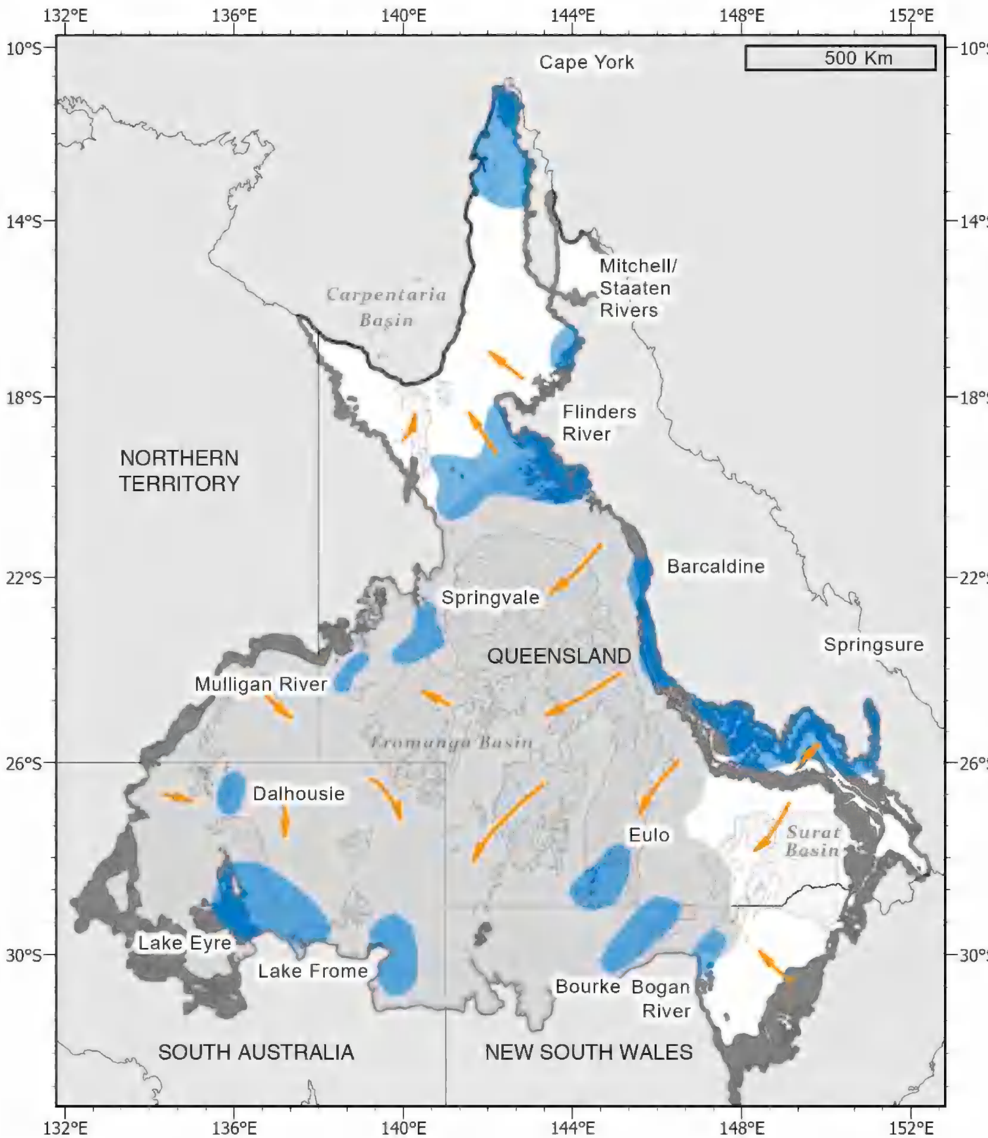
The GAB with sub-basins, major regional clusters of springs (spring supergroups, shown in blue) (Fensham & Fairfax, 2003), local (hatch) and regional recharge areas (dark grey around the GAB periphery), regional flow directions (orange arrows) (Ransley et al., 2015). Source: Flook et al. (2020).



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Author Profiles

Renee Rossini is an early-career ecologist who focuses on the ecology of invertebrates, particularly species endemic to GAB springs, where she completed her PhD in 2018 on how the environmental requirements of endemic molluscs create and maintain their narrow patterns of distribution. She now works across Griffith University, The University of Queensland and the private not-for-profit Queensland Trust for Nature, engaging in spring ecology and conservation through policy, ecological and evolutionary research, and education partnerships.

Angela Arthington is Professor Emeritus in the Australian Rivers Institute at Griffith University, Brisbane. Her research interests span river and fish ecology, the science and management of environmental flows, and the conservation of freshwater biodiversity. Arid-zone wetlands are her favourite research sites. She currently has editorial roles with several international journals and is the Honorary Editor of the *Proceedings of The Royal Society of Queensland*.

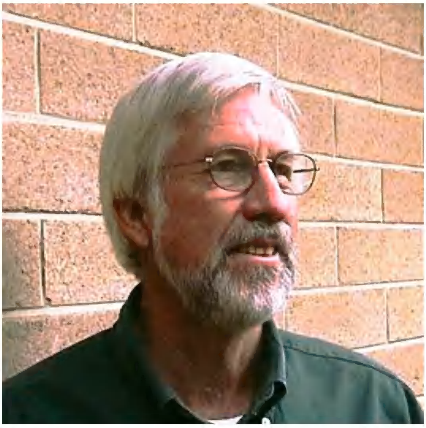
Sue Jackson is Professor of Cultural Geography at the Australian Rivers Institute at Griffith University, Brisbane. Her current research interests include the social and cultural values associated with water, customary Indigenous resource rights, systems of resource governance, and Indigenous capacity building for improved participation in natural resource management and planning.

Moya Tomlinson is a groundwater ecologist who has worked in groundwater planning, policy and research in several Australian jurisdictions.

Craig Walton is a senior policy officer in the Queensland Department of Natural Resources, Mines and Energy. His role is focused on water policy in the Great Artesian Basin; and with a background in plant ecology, Craig is pleased to be overseeing policies and programs targeted at making the basin in Queensland watertight, because of the important ecological and social outcomes that will result from this work.

Steven Flook is Director of Management Strategies and Implementation, Office of Groundwater Impact Assessment, DNRME, Queensland. He is a passionate water resource professional with experience in water planning, cumulative impact assessment, groundwater-dependent ecosystems, science communication, design and implementation of research programs and inter-jurisdictional policy development. His experience relates predominately to investigations in the Great Artesian Basin and the Condamine Alluvium for the Queensland Government.

Obituary for Lynn Brake



24 August 1943 – 21 December 2019

Lynn Brake was an outstanding leader in the sustainable management of the Great Artesian Basin (GAB), Lake Eyre Basin and the GAB springs. His enthusiasm and professionalism were evidenced in national, state and local projects for over 35 years.

Lynn's philosophy – that first-hand experience is the best teacher – meant he worked tirelessly in the field on sustainable water resource management with state and federal governments, regional natural resources bodies, industry groups, communities and land managers across inland Australia.

Lynn moved to Australia in 1971 with a Master of Science from Oregon State University, originally to teach secondary school science. In 1972 he joined Murray Park College of Advanced Education and was the principal driver behind the Outdoor Education movement in South Australia during his tenure there, and later with the Park Management courses at Salisbury College of Advanced Education. His approach equipped trainee teachers and park managers with real-life experiences to personalise their book knowledge. Many South Australian teachers and environmental officers fondly recall their university days with Lynn as their lecturer, and as organiser of camps and field trips that ranged from diving on Yorke Peninsula reefs to bushwalking remote gorges of the Flinders Ranges. Lynn still held a Senior Research Fellowship at the University of South Australia – created in 1992 from the amalgamated Colleges of Advanced Education – at the time of his death.

Lynn's most prominent national role was as a founding and 20-year member of the National Great Artesian Basin Coordinating Committee (GABCC), developing the first national Strategic Management Plan in 2000. Adoption of this plan led to the development and implementation of the Great Artesian Basin Sustainability Initiative (GABSI) dedicated to the restoration and repair of uncontrolled bores and bore drains across the basin. At the conclusion of the GABSI program in 2017, it was estimated that water savings exceeding 250 gigalitres per year had been achieved through the program.

At the state level, Lynn led the preparation and adoption of the South Australia Water Allocation Plan for the Far North Prescribed Wells Area in 2009, covering water extraction from the Great Artesian Basin in South Australia. Maintaining

water in the Great Artesian Basin to sustain mound springs was a central objective of this plan. He was also involved in the multi-million-dollar National Water Commission South Australian-based project Allocating Water and Maintaining Springs in the Great Artesian Basin.

Over several decades Lynn also held a number of other significant state roles focused on the Lake Eyre and Great Artesian Basins, including: Chairperson of the South Australia Arid Area Water Resources Committee; Inaugural Presiding Member of the Arid Areas Catchment Water Management Board; and Chairperson of the Water Advisory Committee (South Australian Arid Lands NRM Board).

Lynn also devoted time and energy to local projects. He had been a supporter of the Friends of Mound Springs group activities in South Australia since the group's inauguration in 2006 and was made a Patron in 2016. It was his positive, calm nature and his outstanding ability to engage well with people and communities that enabled him to bring them along on the journey to improve how water was managed and used in the Far North of South Australia. Lynn was widely respected for his integrity, knowledge, leadership and determination to achieve positive outcomes.

Although Lynn had been undergoing treatment for cancer for many years, he devoted an enormous amount of time and energy in 2018–2019 to a project designed to provide a sound ongoing basis for the management of GAB springs – the development of an Adaptive Management Plan for GAB Springs. A paper describing this plan forms part of this Special Issue (Jensen, Lewis & Lewis, 2020). Lynn was the instigator, inspiration and primary driving force for the project, and he was presented with a copy of the completed project report in December 2019.

Lynn championed GAB springs at a national and state level for many years, and there is no doubt that he made a difference and achieved significant advances in helping to conserve springs. Just before Lynn's death, the Commonwealth Government announced it would establish the Lynn Brake PhD Scholarship in his honour to support the development of future scientists and to help foster links between academia, the wider community and governments.

Author

Craig S. Walton, President, The Royal Society of Queensland (2004–2013).

Dedicated to the memory of scientist, teacher and advocate Lynn Brake